OPTIMIZATION MODEL FOR MAINTENANCE OF TRAFFIC SIGNALS

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by

T.G. SMITH

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

OPTIMIZATION MODEL FOR THE MAINTENANCE

OF TRAFFIC SIGNALS

To: G. A. Leonards, Director
Joint Highway Research Project

October 29, 1965

From: H. L. Michael, Associate Director
Joint Highway Research Project

File: 8-4-30
Project: C-36-17DD

The Final Report attached "Optimization Model for the Maintenance of Traffic Signals" has been prepared by Mr. Thorold G. Smith, Graduate Assistant on our staff. The research reported was approved by the Board on April 22, 1964, and was performed under the direction of Professor J. C. Oppenlander. Mr. Smith also used the research report for his thesis in his MSCE graduate program.

The report presents a suggested traffic signal and flasher maintenance program for the Crawfordsville District. The proposed program was developed using systems analysis techniques and is both practical and economical. A similar analysis would provide similar programs for any other District.

The report is presented to the Board for the record and for acceptance as fulfillment of the research plan.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:bc

Attachment

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Final Report

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by

Thorold G. Smith

Graduate Assistant

Joint Highway Research Project

File: 8-4-30

Project: C-36-17DD

Purdue University
Lafayette, Indiana
October 29, 1965

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ABSTRACT

Smith, Thorold Goddard, Jr. MSCE, Purdue University, January 1966. Optimization Model for the Maintenance of Traffic Signals. Major Professor: Joseph C. Oppenlander

The purpose of this investigation was to develop a comprehensive traffic signal and flasher maintenance program, using systems analysis techniques, that was both economical and practical for the Crawfordsville maintenance district in the State of Indiana. All phases of the corrective and preventive maintenance operations were analyzed to determine the optimal maintenance program. The optimum lamp replacement program, involving the determination of the proper cycle lengths for the most economic group lamp replacements, was determined. The shortest route for preventive maintenance operations was ascertained for several maintenance alternatives, and the most economic option was revealed. An economic analysis was performed to compare the maintenance costs for work executed by State personnel and subcontractors, and recommendations were made concerning allocating additional maintenance responsibilities to subcontractors. Then the staff necessary for effective traffic signal and flasher operation was ascertained for the Crawfordsville maintenance district.

The results of this study of the traffic signal and flasher maintenance in the Crawfordsville district indicates that preventive maintenance is advisable because it affords economic advantages and reduces the probability of failure, thereby improving traffic safety. The proposed maintenance program for the study district includes scheduling group lamp replacements at six-month intervals, using 6000-hr lamps, and allocating maintenance operations to subcontractors where there is a sufficient clustering of traffic signals and flashers.

INTRODUCTION

A major responsibility of highway engineers is to provide for the public a highway system capable of accommodating vehicle and pedestrian travel in a safe, efficient, and economic manner within the desired time and place utilities. In developing this highway system, the engineer is responsible for the planning, design, construction, operation, and maintenance of that system.

In many instances the maintenance function is relegated to a minor position. Limitations in the available resources coupled with the expansion of the planning, design, and construction operations to keep pace with the increasing traffic demands have resulted in a situation where funds and other efforts, necessary for the maintenance of existing facilities, have been diverted to other tasks. In addition, past experiences indicates some difficulty in interesting engineers in the area of maintenance operations. The result is, there is a shortage of qualified men and other resources in a field on which the continued operation of the highway system is predicated.

In the past the maintenance personnel had to use rule-of-thumb warrants, personal experience, or at best component

analysis to determine the maintenance program that utilizes the expected budget allowances. Recent advances in the fields of systems analysis and computer technology have provided the engineer with the tools necessary to analyze various maintenance situations. A complete analysis of all the related factors enables the maintenance engineer to optimize the available men, money, and equipment and insure the proper and safe operation of the system.

The traffic engineer is concerned with a maintenance program applicable to traffic signals and flashers, because the continued and accurate operation of the traffic control devices is necessary for safe and efficient traffic movement. Signal reliability is a necessity because failures create hazards to life and property and increase the maintenance costs by requiring men and equipment to rush to the scene of the failure. In addition, a controller that is not accurate does not facilitate efficient traffic flow, because it is not in the proper operational phase in relation to the other signals and the daily traffic patterns.

A preventive maintenance program reduces the number of traffic signal failures and insures the accurate operation of the controllers. However, the formulation of such a program is beyond the intuitive comprehension of any individual because of the numbers and sophitication of the traffic signals being used. Systems analysis techniques and high-speed

electronic computers permit formulating a comprehensive traffic signal and flasher maintenance program that relates each component to the total operation of the system.

The purpose of this investigation was to develop a comprehensive traffic signal and flasher maintenance program that was both economical and practical for a typical maintenance district in a state highway department. All phases of the corrective and preventive maintenance operations were analyzed to determine the optimal maintenance program. The optimum lamp replacement program, involving the determination of the proper time intervals for scheduling group lamp replacements and the most economic lamp life, was ascertained. The shortest route for preventive maintenance operations was determined for several maintenance alternatives, and by comparing the anticipated annual costs, the most economic option was revealed. An economic analysis was also performed to compare the maintenance costs for work executed by state personnel and by subcontractors. Recommendations were made concerning the advisability of allocating additional maintenance responsibilities to contractors. The staff necessary for effective traffic signal and flasher operation was ascertained from the results of the lamp replacement study, the optimal routings for preventive maintenance, and the comparison of maintenance performed by state personnel and contractors.

A scientific maintenance program enables the traffic engineer to discharge his principle assignment of providing

safe, efficient, and economic travel by insuring that the traffic signals and flashers are dependable and operating in accordance with the predetermined schedules. The investment in traffic control devices is protected by eliminating the deterioration of equipment and the resulting costly failures caused by a policy of neglect. Traffic signals that are clean, well painted, and in proper working condition afford the traffic engineering profession a medium for establishing good public acceptance.

REVIEW OF LITERATURE

The subject of maintenance appears quite frequently in industrial trade magazines but rather infrequently in traffic engineering literature. This literature review is confined to those articles which apply to this research investigation. The following topics are discussed.

1. Traffic signal maintenance procedures.
2. Industrial maintenance concepts.
3. Model building.
4. Minimum path algorithms.
    a. Point-to-point paths.
    b. Traveling salesman paths.

Traffic Signal Maintenance Procedures

Several papers and reports have been written on the subject of traffic signal maintenance. These articles have generally been prepared as guides or suggestions in the formulation of routine maintenance programs.

A primary concern of most maintenance programs is determining the optimal period for the replacement of traffic signal lamps. The American Association of State Highway Officials

(A.A.S.H.O.) recommends a regular lamp replacement schedule that is less than the rated (average) lamp life. The factors involved in the economic determination of scheduling group lamp replacements are:

1. Failure probabilities for the lamps with different manufacturers rated lives,
2. The effect on lamp life of the difference between the voltage at the lamp socket and the rated voltage for the lamp, and
3. The reduction of lamp life expectancy due to the vibrations in normal operation and the lamp handling. (21)*

F. J. Meno concurs with the A.A.S.H.O. policy and says that if the optical units (lenses, lamps, and reflectors) are regularly cleaned, it is possible to apply up to 5v less than the rated lamp voltages without suffering poor visibility. This policy has the effect of lengthening the actual rated lamp life under field conditions. (24) The relationship of voltage to lamp life, wattage, and lumens is illustrated in Fig. 1. (17)

The controller is the second item to be considered in a comprehensive traffic signal maintenance program. Controllers

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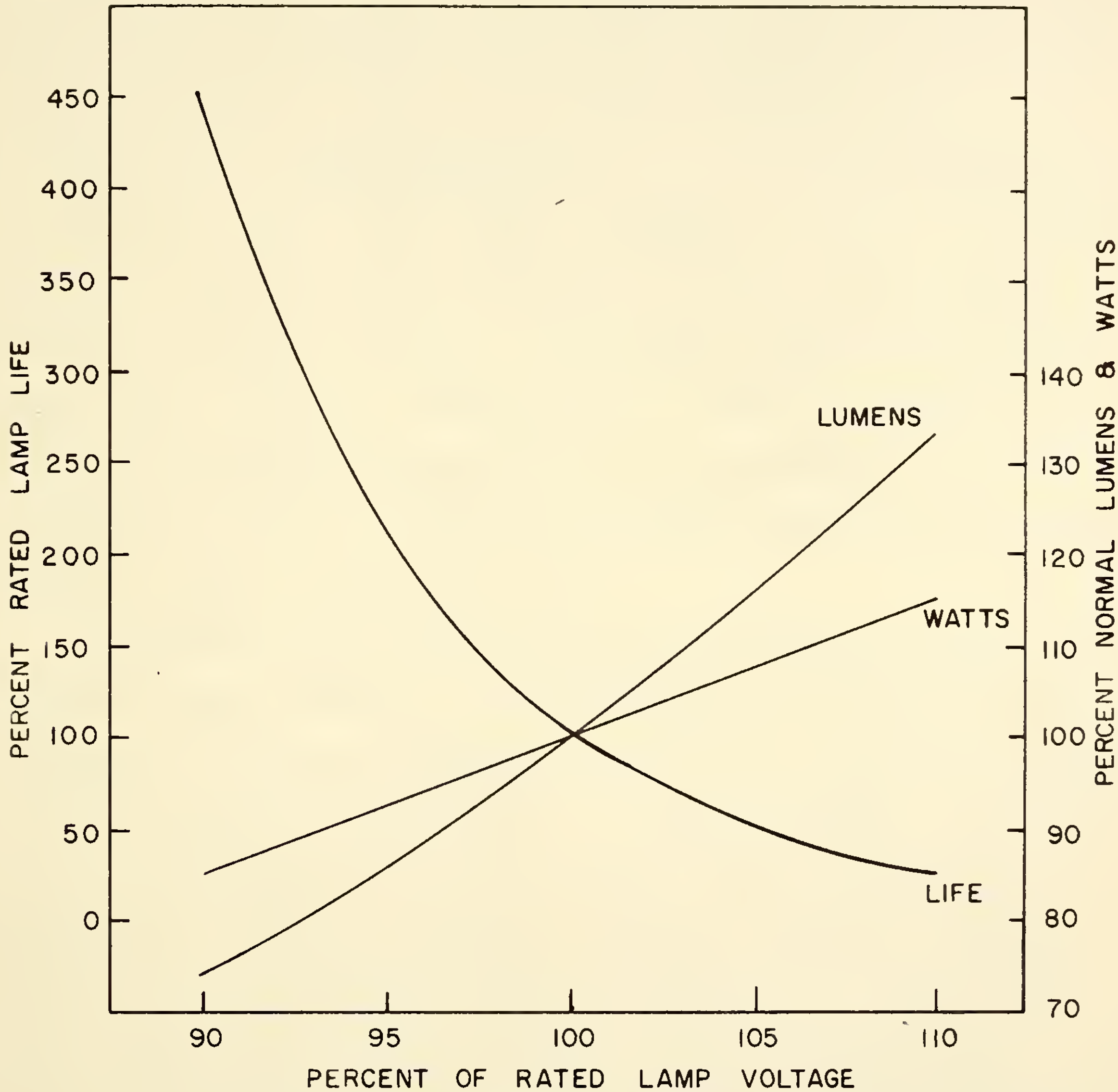
* Numbers in parentheses refer to items in the bibliography.

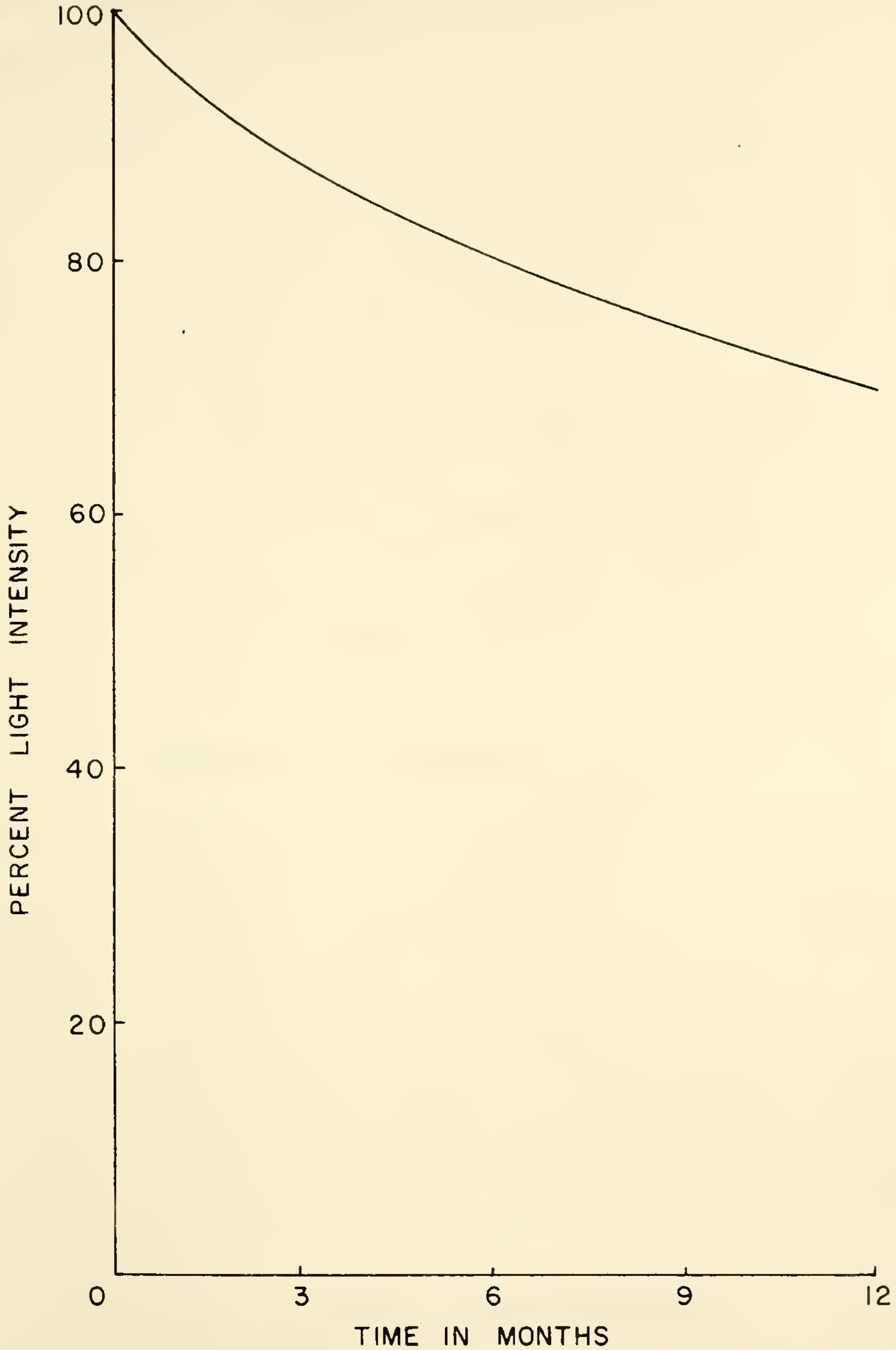


LIGHTING MAINTENANCE MANUAL, Champion Lamp Works

FIG. I EFFECT OF VOLTAGE ON INCANDESCENT LAMP LIFE, LUMENS AND WATTAGE.

must be periodically maintained to assure effective operation. The American Association of State Highway Officials says that controllers shall be carefully cleaned and serviced at least as frequently as specified by the manufacturers and more frequently if experience proves it necessary. (21) In an article for The American City, J. E. Hartley suggests that each unit in the signal system including all master controllers should receive a yearly in-shop over haul. This complete overhaul includes cleaning, lubricating, and replacing all worn parts, then the controllers are tested to determine their reliability and operating characteristics. (13) Controllers are most reliable when cleaned and checked for wear at least every six months. (24)

To maintain the effectiveness of the traffic signal as a traffic control device, it is necessary to consider periodically cleaning the lamps, reflectors and lenses. Optical units that are not regularly cleaned have a 60 to 80 percent reduction in visibility over a period of years. (24) In air that is relatively free from dust and corrosive industrial exhaust the loss of light may be considered similar to experience with closed street light fixtures. Fig. 2, illustrating the experience with closed street light fixtures, shows age has a decreasing effect on light intensity due to the washing action of rainfall. (40) A.A.S.H.O. suggests that the optical units should be cleaned at least once every six-months and



CORRESPONDENCE, GENERAL ELECTRIC COMPANY MARCH 25, 1965

FIG. 2 REDUCTION IN LIGHT INTENSITY DUE TO DIRT ACCUMULATION.

that the lenses and reflectors should always be cleaned when lamps are replaced, unless the last regular cleaning has been very recent. (21)

The last phase in a comprehensive maintenance program is to schedule periodic painting of the traffic signal equipment at intersection locations. Painting is necessary to protect the traffic signal from rust and corrosion, and to assure that the traffic signal appears clean and well maintained. All traffic signal appurtenances above the ground should be painted at least once every two-years, and the painting should be more often if it is needed to prevent corrosion and to maintain a good appearance. (21)

Industrial Maintenance Concepts

A basic industrial maintenance problem is concerned with replacement. The problem of replacement can be subdivided into two distinct categories. The first situation is concerned with the deterioration of captial equipment due to old age and obsolescence. N. N. Barrish in his simplified model of reality delimits the effects of increasing age on most capital items.

1. Maintenance and repair costs increase.
2. The operate rate decreases and the operating costs increase.
3. The income for products or services decreases because the quality of the service is declining.

4. The cost of operating improved machines as compared with deteriorating facilities decreases.
5. There are decreasing receipts for products or services because the relative quality declines as compared with the higher quality product produced by improved machines.
6. There is possible obsolesence of products or services on a gradual or sudden basis depending on technological changes.

In the simplified model of reality the pattern of deterioration due to increasing age is not uniform nor does the same pattern hold true in all cases. (3)

The second replacement problem involves planning for items that fail completely. These items either operate, or they fail to perform their intended functions. The loss of usefulness in sudden and complete without the occurrence of obsolesence. In many instances the failure characteristics of an item such as a light bulb is subject to specified mortality curves. If the lamps fail according to some mortality curve a scheduled program of group replacement can be determined. (32)

A fundamental purpose of maintenance operations is increasing the reliability of the system being considered. Improved reliability is important because in many cases the equipment being maintained are finite in number. With limited populations it is possible that a large portion of the machines are simultaneously in need of repair. To overcome this

possibility, E. S. Buffa lists four industrial practices that increase the system reliability.

1. Increase the capacity of the repair facilities to reduce the possibility of forming a queue of items needing maintenance.
2. Utilize preventive maintenance where practical to replace critical parts before they fail.
3. Provide slack in the system at critical points. This requirement allows an excess of capacity so that some machines can be out of operation without causing excessive delays to the production operation.
4. Make the machines more reliable through improvements in engineering design. (5)

To determine the best method of improving the system reliability, individual components of the system must be studied to ascertain their effects on the entire system.

The maintenance operations best suited for various machines are determined by analyzing the patterns of failure. P. M. Morse has described three basic machine types according to their failure characteristics. Some machines with few moving parts tend to break-down at the end of a constant time interval. Another class of machines has a failure pattern approximated by exponential curves. These machines have many moving parts and depend on adjustments that are randomly destroyed. The last category of machines has a hyper-exponential distribution of failures because the ability of

these machines to perform properly depends on one or more fine adjustments. If these adjustments are done correctly the machine will operate in an acceptable manner for a long period of time. If the adjustments are incorrectly performed the machine may soon need readjustment.

Determining a comprehensive maintenance program is dependent on analyzing the time distribution curves for maintenance and repair operations. The shape of the repair-time curve varies considerably from operation to operation depending on the nature and complexity of the repair task. For preventive maintenance the mean duration of the work is generally shorter than for corrective work. The preventive maintenance operation, because it is planned in great detail, generally has less variability than the corrective maintenance tasks.

If preventive maintenance is to have any real value then the machines must be in as good an operating condition after preventive maintenance as after corrective repairs. That is, it is impossible to determine from the behavior of the machine whether the previous maintenance was a repair or a preventive operation. If any difference exists between corrective repairs and preventive maintenance, than the inferior procedure is evaluated to determine the reasons for its inadequacy. (25)

Preventive maintenance should be scheduled when a machine has low variability in the breakdown-time distribution. Therefore, many failures are prevented, and infrequent use of the reapir operation results when preventive maintenance

is planned short of the average breakdown time. Failures are just as likely after maintenance as at any later time for an exponential breakdown distribution. The only way to reduce the number of breakdowns is to operate the machine less often per unit time. Preventive maintenance for the exponential failure distribution reduces the number of breakdowns by lessening the amount of running time. Breakdowns distributed with great variability necessitates scheduling inefficiently short maintenance cycles to forestall most of the failures. In addition, preventive maintenance planned for machines with wide variations in the breakdown distribution is likely to increase the number of failures, because tinkering with these machines augments the probability of failure. (5,25)

Model Building

The development of theories and laws of nature involves finding general models of reality. Advancement in the fields of engineering and economics is predicated on developing better models of reality which are used to explain present situations and to predict future behavior.

Recent advances in mathematical and statistical methods and the development of high-speed data processing equipment has made it possible to effectively use model building to simulate reality in many areas of economic decision making.

Present-day models are more complex and realistic but still within the capacities of the new electronic computers.

There are three commonly recognized model types. Models which resemble reality in a physical sense are the first class of paradigms. These models are physical representation of proposed designs. The duplications are full-size as the prototypes for automobiles, smaller versions of reality like ship hulls tested in towing tanks, or scaled-down operations as in pilot plants.

Analogous models tend to deviate from reality, but all important properties of the actual situation are represented for analytic purposes. For example, a road map may have heavy solid lines to indicate highways of four or more lanes, light solid lines to show primary highways, and dashed lines to indicate all other roads. The map provides an analogy of the highway system but does not represent the actual appearance of this system. Another example of analogous models are flow charts and logic diagrams where each phase of an operation is represented in the proper chronological order. However, there is no indication of the physical size and shape of the components in the system portrayed by the flow chart.

Mathematical models are even further removed from the physical appearance of reality. Symbolism is used in these models to specify the significant relationships, and mathematical equations describe the manner in which these relationships behave in reality.

The use of models to simulate reality offers several important benefits. Several proposed changes in operation can be tried without disrupting present operational procedures. The practicality of many alternatives can be tested by model analysis in a relatively short period of time. However, limitations of money and time preclude using production facilities for testing similar alternatives.

Model building is not a panacea for the solution of all engineering problems. The development of realistic models is limited to those situations where model building sufficiently simulates the important properties of the system. Then, the expected benefits and the model costs are related to determine if there is economic justification for a simulation model. (3, 5, 25)

Minimum Path Algorithms

To find the best maintenance program for traffic signals in a maintenance district, it is necessary to plan and schedule preventive maintenance operations to minimize the total travel distance. The most common method optimizing travel distance is to use minimum path algorithms.

Until recent years mathematical approaches to the minimum path problem were abandoned because numerous calculations were necessary. In most cases the vast number of calculations required negated any benefits derived from knowing the

minimum path. However, computers and data processing equipment have been developed so economic determination of an optimum route is feasible.

Before an optimum path can be determined, a criteria for measuring the path must be established. The optimal criteria is to maximize economic and social benefits as well as customer good will and satisfaction, but it is not practical to use this criteria, so the elements recommended for determining the minimum path are:

1. Distance,
2. Time, and
3. Travel cost.

Point-to-Point Paths

Routing problems are classified in two groups. The first category is point-to-point paths, that is, problems involved in the determination of the shortest route between two points. The location of the shortest route is only a problem where there are a number of paths and the shortest route is not obvious.

There are two methods of determining the shortest route between two points. The first technique developed by A. Shimbel and R. Bellman is to use a matrix or rectangular array of numbers to depict the highway network through which the shortest route is desired. Each entry in the matrix is

represented by a double subsripted letter. The first subscript designates the row and the second the column of an entry in the matrix. The entries represent the distance between the corresponding row and column nodes. In the initial matrix the entries in the array are the distances between two nodes connected by one link. When the two nodes are not connected by a single link, the entry a_{ij}, is arbitrarily established at some value much larger than any number in the matrix.

The table described above is used to generate a new matrix whose entries are labeled with the same convention. Each new entry, b_{ij}, is computed by choosing the minimum sum $a_{ik} + a_{kj}$ where k is the row or column index of every node. If b_{ij} is different from a_{ij} the numerical value and the associated k are recorded for each entry. Matrices are generated in this manner until two consecutive matrices are equal. The final matrix is an array of the shortest distances between the corresponding row and column nodes. (22,38)

The second method, proposed by B. V. Martin, G. B. Dantizig, and the Road Research Laboratory is similar to dynamic programming techniques. This minimum path algorithm is used primarily where a few routes are to be located. The network is represented by a list of all links connecting each node and the corresponding distances. The links are then arranged in ascending order, and the shortest routes are

found by fanning from one terminal adding one link at a time. The result of this procedure is true of the shortest routes from the starting point. (38,22)

Traveling-Salesman Paths

The second class of minimum path problems involves visiting a number of points connected by the shortest possible route. This situation is analogous to the problem of a salesman who has to call on a number of customers in different locations before returning home. A salesman starting in one city wishes to visit each of n-1 other cities once and then return to the original city traveling the shortest possible distance for the entire tour. This travel can be accomplished in $(n-1)!$ possible tours, one or more of which is a minimum solution.

This problem has been solved by several different approaches. One procedure necessitates the calculation of every possible tour. This technique has the advantage of insuring the selection of the optimal route. However, even for a small number of cities large numbers of computations are required for determining the minimum path.

A second approach for solving the traveling salesman problem combines intelligently directed search with random search. The directed search allows a reduction in the calculation costs, and the random search prevents a suboptimization of some parts of the problem. The primary weakness of this

approach is that there is no assurance of finding the absolute minimum path.

The general procedure is to generate a random permutation of the nodes to be visited. In the simplest case the cost of this random tour is calculated. Then a second random tour is generated, and the cost is found. The costs of the first tour and the second tour are compared, and the minimum tour is retained. The process of calculating costs for random tours and comparing them with the shortest route obtained continues until the operator is satisfied the minimum path has been found. (10,31)

A more sophisticated approach is to consider inverting the first and second elements of the random tour. A new tour length is computed, and it replaces the original tour if the new tour length is shorter. In either case, the second and third elements are inverted to form a new tour, and again the lengths are compared. This process of inverting pairs and comparing lengths is continued for the complete array of the random tour. After the shortest tour for the original random tour is found, the process starts again with the generation of a new random tour. (31)

Another variation of this technique is to assign nodes to a tour by a random process. Instead of initially writing the complete tour, only the first three nodes are written. The fourth node is then placed in the tour so that the route

including this node is a minimum. This process of adding and testing new nodes continues until the tour is completed. Then, as before a new random set is generated and the process continues until the operator is satisfied with the degree of optimization achieved. (10)

PROCEDURE

The traffic-signal maintenance activities in a selected maintenance district were observed to determine the time patterns of traffic signal operations in regard to their maintenance characteristics. Maintenance of traffic signals was formulated into a system of related components to permit the development of an optimum traffic signal maintenance program in the study district. Statistical estimations and various statistical tests were used to appraise the findings and to develop the necessary relationships.

Site Selection

The selection of a suitable study site involved the consideration of several important factors. First, the study area must be representative of all the maintenance districts found in the State of Indiana. Second, to compare the economies of traffic signal maintenance by state personnel and subcontractors it was necessary that both forms of maintenance exist within the study area. Third, a district readily accessible from Lafayette was necessary for consultation with the maintenance personnel concerning the existing maintenance program, data collection, and verification of

data. The Crawfordsville maintenance district in the State of Indiana was selected because this location satisfactorily fulfilled the three necessary qualifications for a suitable study area.

The Crawfordsville maintenance district, illustrated in Fig. 3, has three principle urban centers, Terre Haute, Lafayette, and West Lafayette. The remainder of this district is predominantly rural with a number of small cities and towns. The traffic signals in the three major cities are maintained by subcontractors. Both preventive and corrective maintenance is performed in these cities by subcontractors, except in West Lafayette where state forces are responsible for the preventive maintenance.

The distribution of these traffic control devices is presented in the following outline and illustrated in Fig. 4:

1. Lafayette - 21 signals and 1 flasher,
2. Terre Haute - 40 signals and 4 flashers,
3. West Lafayette - 13 signals, and
4. The remainder of the district - 56 signals and 42 flashers.

Data Collection

Because little information was available on the maintenance of traffic signals, a data form was designed to permit the collection of the necessary maintenance details. This form is illustrated in Fig. 5. A description of the information recorded for the daily maintenance of traffic signals

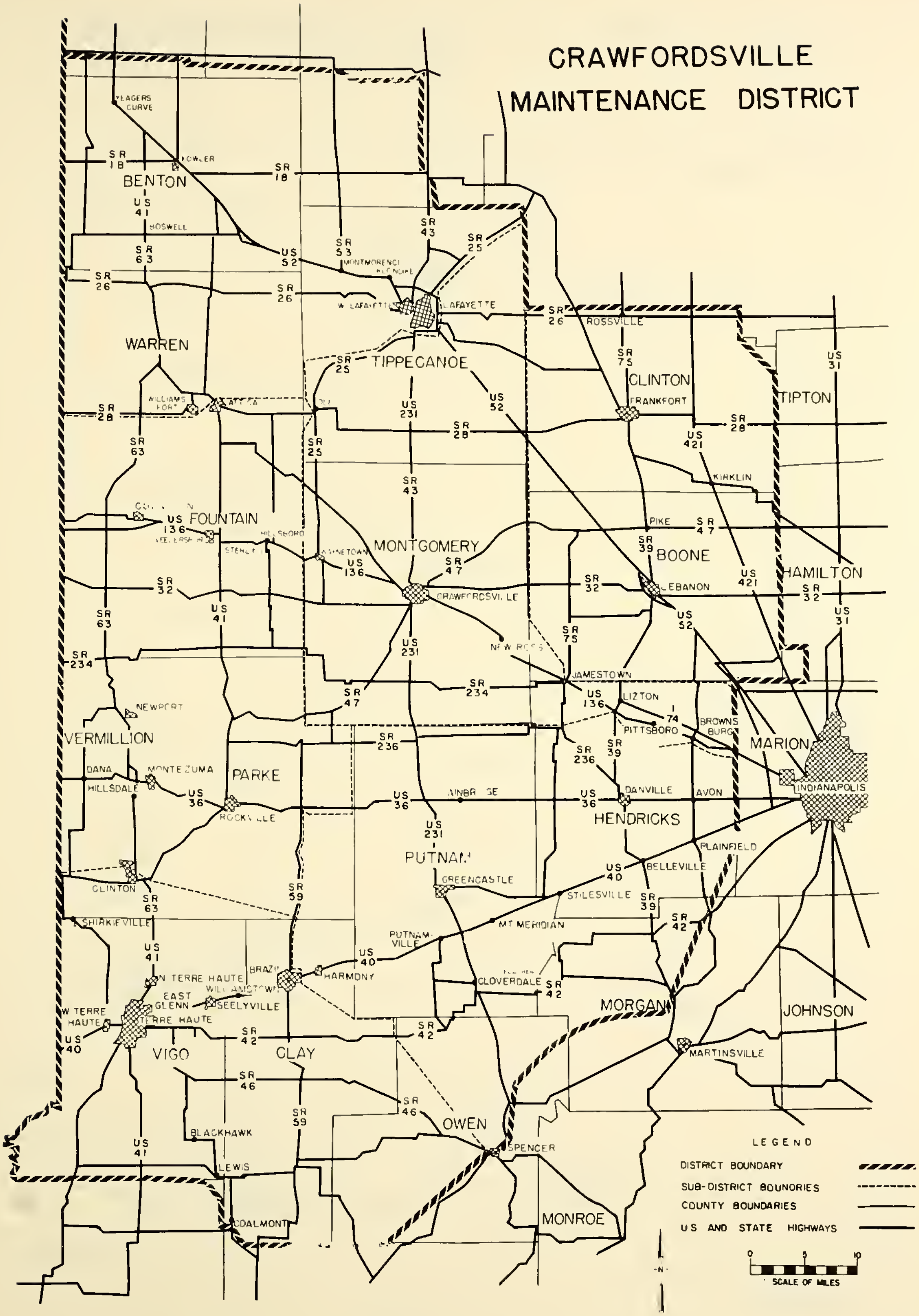
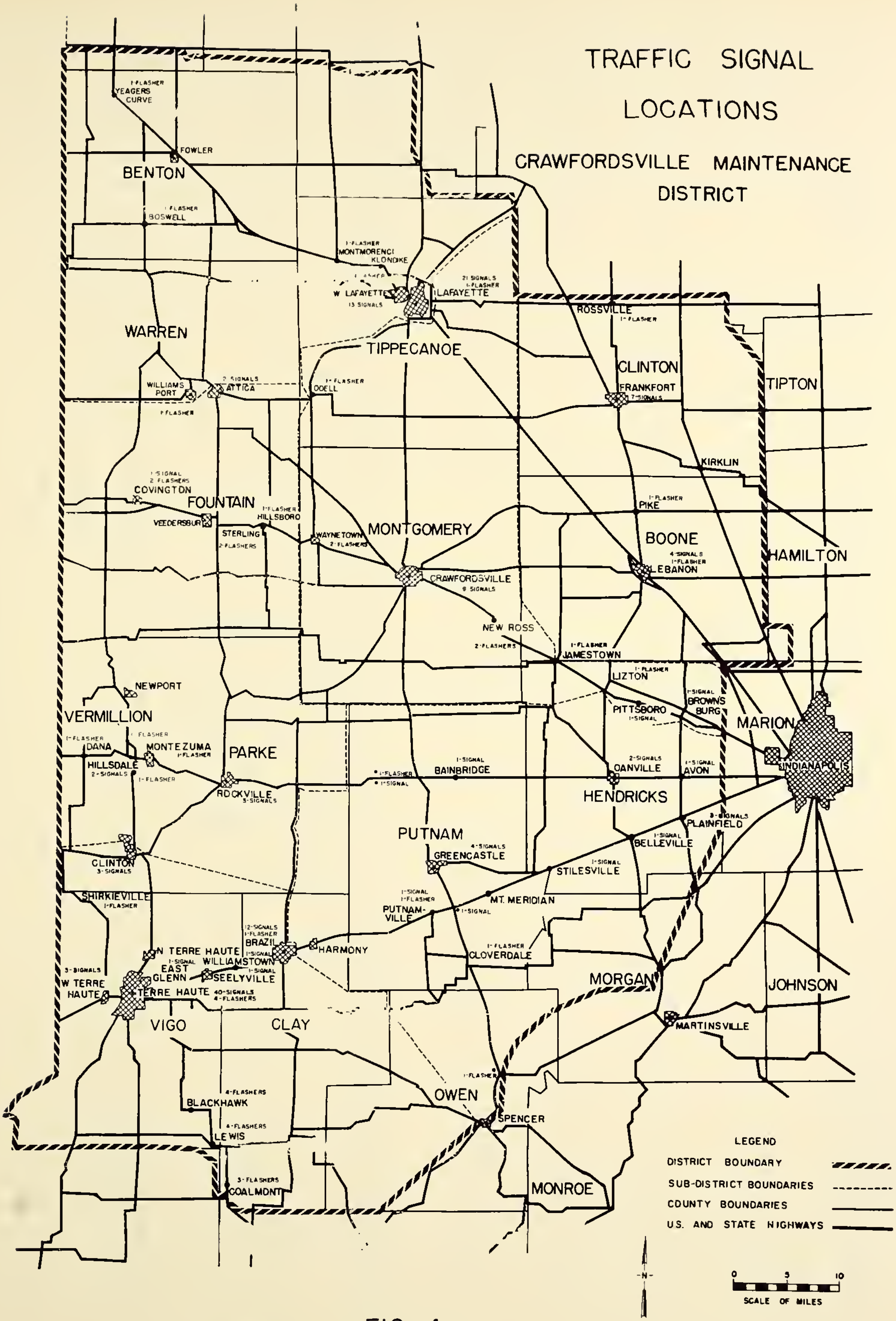

CRAWFORDSVILLE MAINTENANCE DISTRICT
BENTON
WARREN
TIPPECANOE
CLINTON
TIPTON
FOUNTAIN
MONTGOMERY
BOONE
HAMILTON
VERMILLION
PARKE
MARION
HENDRICKS
PUTNAM
VIGO
CLAY
MORGAN
JOHNSON
OWEN
MONROE
LAFAYETTE
FRANKFORT
LEBANON
INDIANAPOLIS
TERRE HAUTE
MARTINSVILLE
SPENCER
GREENCASTLE
DANVILLE
JAMESTOWN
PITTSBORO
PLAINFIELD
BELLEVILLE
ROSSVILLE
KIRKLIN
CLOVERDALE
COALMONT
LEWIS
BLACKHAWK
HARMONY
SEELYVILLE
CLINTON
NEWPORT
LEGEND
DISTRICT BOUNDARY
SUB-DISTRICT BOUNORIES
COUNTY BOUNDARIES
US AND STATE HIGHWAYS
SCALE OF MILES

FIG. 3



TRAFFIC SIGNAL LOCATIONS
CRAWFORDSVILLE MAINTENANCE DISTRICT
BENTON
WARREN
TIPPECANOE
FOUNTAIN
MONTGOMERY
CLINTON
TIPTON
BOONE
HAMILTON
VERMILLION
PARKE
PUTNAM
HENDRICKS
MARION
VIGO
CLAY
MORGAN
JOHNSON
OWEN
MONROE
YEAGERS CURVE
FOWLER
BOSWELL
MONTMORENCI
KLONDIKE
W LAFAYETTE
LAFAYETTE
ROSSVILLE
WILLIAMS PORT
ATTICA
ODELL
FRANKFORT
KIRKLIN
COVINGTON
VEEDERSBURG
HILLSBORO
STERLING
WAYNETOWN
PIKE
LEBANON
CRAWFORDSVILLE
NEW ROSS
JAMESTOWN
LIZTON
NEWPORT
PITTSBORO
BROWNS BURG
DANA
MONTEZUMA
HILLSDALE
ROCKVILLE
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MT. MERIDIAN
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BRAZIL
HARMONY
N TERRE HAUTE
WILLIAMSTOWN
EAST GLENN
SEELYVILLE
CLOVERDALE
W TERRE HAUTE
TERRE HAUTE
MARTINSVILLE
BLACKHAWK
LEWIS
SPENCER
COALMONT
LEGEND
DISTRICT BOUNDARY
SUB-DISTRICT BOUNDARIES
COUNTY BOUNDARIES
U.S. AND STATE HIGHWAYS
SCALE OF MILES

FIG. 4

DAILY MAINTENANCE REPORT

DATE ____________ CREW ____________ EQUIPMENT ____________

WEATHER CONDITIONS AM ____________ TEMPERATURE AM ______ PM ______

WEATHER CONDITIONS PM ____________ MAINTENANCE CONTRACTOR ____________

LOCATION OF TRAFFIC SIGNAL	NUMBER OF MILES TO SIGNAL LOCATION	TIME OF CALL EMERGENCY ONLY	TIME OF DEPARTURE TO TRAFFIC SIGNAL	TIME OF ARRIVAL AT TRAFFIC SIGNAL	TIME WORK STARTED ON TRAFFIC SIGNAL	TIME WORK ENDED ON TRAFFIC SIGNAL	PARTS REPLACED		NATURE OF WORK DONE
							QUANTITY	TYPE	

FIG. 5 DATA FORM USED TO COLLECT THE NECESSARY TRAFFIC SIGNAL AND FLASHER MAINTENANCE DETAILS.

and flashers are summarized in the following outline.

1. The titles and number of men on the work crews and the major equipment used for the maintenance operation were recorded to determine the field costs for the maintenance operations.
2. The name of the group maintaining the traffic signals was entered to assign the work performed to the proper agency.
3. The emergency call time and the time of departure were recorded to determine the time lag between the notification of a failure and the departure for the failure site.
4. Travel time was computed by noting the difference between the departure and arrival times.
5. The time intervals required to complete the various maintenance tasks were obtained by using the times the work started and ended for the maintenance operations.

Supplementary information was collected through consultation with the Indiana State Highway Commission and correspondence with several traffic signal lamp manufacturers.

Data Analysis

The data analysis was designed to give estimates of observed maintenance conditions for the Crawfordsville

maintenance district. Models approximating the actual maintenance situation were formulated, and the optimum traffic signal maintenance program was determined by using these models.

Lamp Replacement

Two steps were involved in building a model that predicts the optimal lamp replacement time. A probabilistic expression was first developed to approximate the expected traffic signal lamp operation. Several assumptions were made to formulate this expression. All traffic signal lamps, regardless of manufacture or rated life, have the same type of failure curve. Therefore, lamp mortality curves that are based on percentage of rated life can be used for all traffic signal lamps. (39,40,41)

The actual life of a lamp used in the field was assumed to have a service life that is 10 percent less than the manufacturer's rated life. The manufacturers ratings are based on lamp tests conducted under ideal laboratory conditions. In the field the conditions are far from ideal. Power surges and vibrations caused by handling, wind, and traffic are the principle causes of the differential between the rated lamp life and the actual life. To account for this variation, the rated lamp life is often reduced 20 percent if the field conditions are very severe and 10 percent if these conditions are normal. (40)

The mortality curve shown in Fig. 6 was assumed to be normally distributed with a mean of 100 percent for the rated life and a standard deviation of 25. A Chi-square test was used to determine if the observed curve was a normal distribution. The results of this test produced a calculated Chi-square of 0.0043. This value is not significant at the 5-percent level with 27 degrees of freedom. Therefore, the mortality curve of traffic signal lamps was considered as a normal distribution in the rest of this investigation. In addition to the assumption of normality, the life of a lamp was assumed to be independent from that of the other lamps.

With these assumptions the following model was developed:

Notations

X = cost per replacement cycle per lamp.

X_t = cost per hour of operation per lamp.

t = lamp relacement period in hours.

c = cost of replacing a lamp in group replacement.

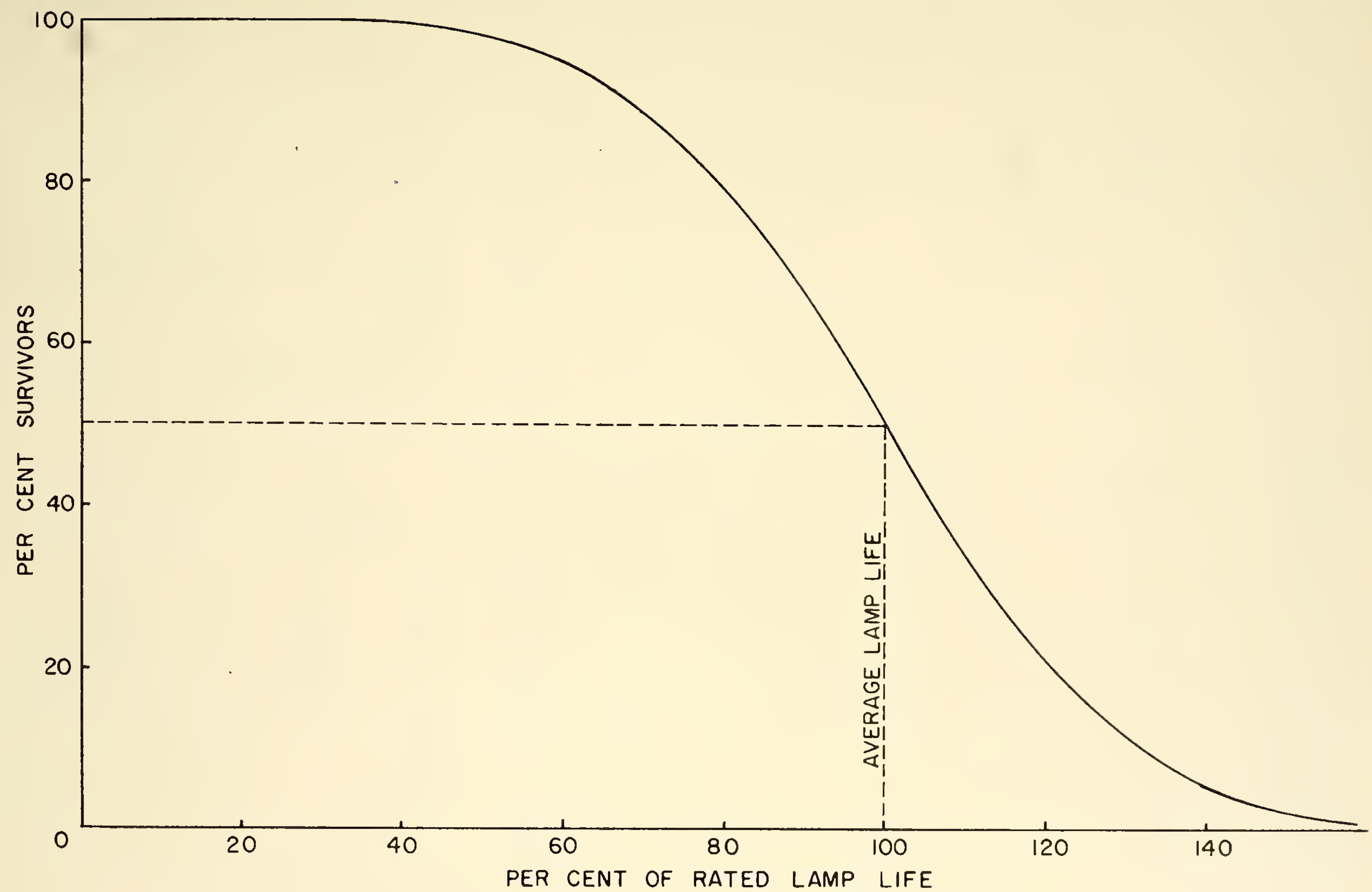
k = cost of replacing a lamp at failure.

T_i = lamp life in hours of ith lamp when $T \sim N(100,25)$, where the lamp lives are independent.

$A_n = T_1 + T_2 + \ldots\ldots\ldots + T_n < t$

$B_n = T_1 + T_2 + \ldots\ldots\ldots + T_n + T_{n+1} > t$

$B'_n = T_1 + T_2 + \ldots\ldots\ldots + T_n + T_{n+1} < t$



CORRESPONDENCE, GENERAL ELECTRIC COMPANY MARCH 25, 1965

FIG. 6 ESTIMATED MORTALITY CURVE (BASED ON TOTAL AVERAGE PRODUCT).

Postulate: In all cases the occurrence of event B'_n is predicated on the occurrence of event A_n, or B'_n is included in A_n.

Corollary: $P(A_n B_n) = P(A_n) - P(B'_n)$

Derivation:

$$X = c \text{ if } T_1 < t$$

$$X = c + K \text{ if } T_1 < t < T_1 + T_2$$

$$\begin{matrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{matrix}$$

$$X = c + nk \text{ if } A_n \text{ and } B_n \text{ occur}$$

$$X = cP(T_1 > t) + \sum_{i=1}^{n} (c+ik)\, P(A_i B_i)$$

$$X = cP(T_1 > t) + \sum_{i=1}^{n} (c+ik)\, (P(A_i) - P(B'_i))$$

$$X = cP(T_i > t) + c \sum_{i=1}^{n} (P(A_i) - P(B'_i)) + \sum_{i=1}^{n} ik\, (P(A_i) - P(B'_i))$$

But:

$$c = cP(T_1 > t) + c \sum_{i=1}^{n} (P(A_i) - P(B'_i))$$

Therefore:

$$X = c + \sum_{i=1}^{n} ik\, (P(A_i) - P(B'_i))$$

Computational Form:

$$X_t = \frac{c}{t} + \frac{1}{t}\Big\{ k \left[(P(T_1 < t) - P(T_1 \_ T_2 < t) \right]$$

$$+ 2k \left[(P(T_1 + T_2 < t) - P(T_1 + T_2 + T_3 < t) \right] + \ldots$$

$$\ldots + nk \Big[(P(T_1 + T_2 + \ldots + T_n < t)$$

$$- P(T_1 + T_2 \ldots + T_n + T_{n+1} < t) \Big] \Big\}$$

The above replacement model determines the hourly cost for a single lamp. The use of elementary probability indicates that the cost per hour for n lamps is equal to the expression nX_t.

The second step in the formulation of the replacement model is to determine the group and failure replacement costs. The cost of traffic signal lamps is an important consideration in calculating the replacement costs. Lamps in the 60 to 69 w range with rated lives of 2000 to 8000 hr are of primary interest to the maintenance personnel in the Crawfordsville district. The prices of these lamps vary linearly with the rated lamp life as shown by the function:

$$Y = 0.001X + 28.5$$

where Y = cost per lamp in cents, and

X = rated lamp life in hours.

Governmental agencies are given a discount of about 50 percent when large quantities of traffic signal lamps are purchased. (40) As a result of this discount, the function estimating the lamp cost for the State of Indiana can be expressed as:

$$Y = 0.0005X + 14.25$$

The cost of replacing a lamp in a group replacement program was determined. In the Crawfordsville maintenance district 1896 lamps are maintained by state personnel. The total time required to change lamps on a group replacement program, including travel time is 130 hr. The development of this group replacement program is presented in the Results. The cost of replacing a lamp in a group replacement program for the Crawfordsville maintenance district is shown in Table 1.

The cost of changing a lamp at failure is the next step in preparing information for the lamp replacement model. The mean distance of the lamps from the district maintenance offices was calculated. In determining the average distances for the Crawfordsville district, the lamps were classified by their uses. For the 160 lamps used in flashers the average distance of these lamps from Crawfordsville is 36.26 mi. The mean distance of the 1510 lamps used in traffic signals is 30.66 miles from Crawfordsville. A weighted mean of 31.20 miles was calculated by pooling all lamps used to estimate

TABLE 1. LAMP REPLACEMENT COSTS

GROUP REPLACEMENT COSTS

Cost of Labor (2 men @ \$2.45 per hour) x 130 hr	\$ 637.39
Cost of Equipment (1 truck @ \$5.00 per hour) x 130 hr	650.40
Cost of Lamps (current price) (\$0.16 per lamp) x 1896 lamps	303.76
Total cost of group replacement	\$1,591.55
Total cost of group replacement per lamp	\$ 0.84

FAILURE REPLACEMENT COSTS

Cost of Labor (2 men @ \$2.45 per hour) x 1.84 hr	\$ 9.02
Cost of Equipment (1 truck @ \$5.00 per hour) x 1.84 hr	9.20
Cost of Lamp (current price) \$0.16 per lamp	0.16
Total cost of changing a lamp at failure	\$ 18.38

the average distance of lamps from the maintenance headquarters in Crawfordsville.

An estimation of the travel time is required to determine the costs for lamp replacement at failure. The relationship expressing the distance traveled in minutes is:

$$Y_C = 1.437X + 7.775$$

where Y_C = travel time in minutes, and

X = distance traveled in miles.

The development of this function is presented in the Optimal Sequencing for Preventive Maintenance section of the Procedure.

For a mean travel distance of 31.20 miles the one-way travel time is 52.69 min, and the total two-way travel is 105 min. The expected time required to change a single lamp at failure was found to be five minutes. Therefore, the total time spent changing a lamp that has failed is 110 min or 1.84 hr. The cost of replacing a lamp that has failed is illustrated in Table 1.

To complete the preparation of information for the lamp replacement model, a realistic estimation for the number of hours that lamps burn under field conditions was needed. The annual burning times for traffic signal lamps in various uses are summarized in Table 2. These time estimates are based on above average conditions of usage for traffic signals and

TABLE 2. LAMP BURNING TIME ESTIMATES FOR VARIOUS TRAFFIC SIGNAL AND FLASHER USES

Lamp Use	Percent of Time	Hour per Year
Flasher	58	5080
Traffic Signal		
Red	50	4380
Green	42	3680
Amber	8	700

flashers located in the Crawfordsville maintenance district.

The probabilistic model was written in FORTRAN IV, and the calculations necessary in determining the optimal replacement period were performed on the IBM 7094 computer. This program and a technical description of the data input are presented in Appendix A.

The analysis using the replacement model was performed in two ways. Determining the relationship for the optimal replacement time and the percent of rated life was the first analysis. The ratios of replacement costs (group replacement versus replacement at failure) were incremented to find the pattern of variation in the optimal lamp replacement time. The second analysis used specific information for the Crawfordsville district to determine the expected hour costs of using lamps of various rated lives.

Optimal Route Sequencing for Preventive Maintenance

The optimal sequencing of preventive maintenance is determined by a model that simulates the activity of the maintenance crews. The model is predicated on realistic estimations of various factors that influence the work patterns of the maintenance personnel.

The maintenance model is composed of several principal parts. The first section estimates the time required to perform the various maintenance functions. As evidenced from

the field observations, a primary preventive maintenance operation includes changing the signal lamps, cleaning the lenses and reflectors, and cleaning and oiling the controller. The expected work time for this preventive maintenance on a traffic signal installation was 40 min with a standard deviation of 24 min. For a flasher installation the maintenance is expected to take 13 min with a standard deviation of nine minutes.

Another maintenance operation is painting the traffic control installation. The average work time for painting a traffic signal installation is 133 min with a standard deviation of 40 min. Painting a flasher complex takes an average of 37 min with a standard deviation of 13 min.

Data was not available for the combined tasks of signal head and controller maintenance, and of painting the traffic control installation. The expected work times were determined by assuming that the controller and signal head maintenance and the painting operation were independent. This assumption of independence, where the means and variances are additive, is not totally correct. When these two operations are scheduled at the same time, some tasks no doubt, need only be performed once. For the purposes of this investigation, this duplication was considered minimal and thus neglected. The expected work time for the traffic signals became 173 min with a standard deviation of 47 min. For the flashers the average work time was 50 min with a standard deviation of 13 min.

The possibility that the maintenance operation required more than the scheduled time was considered as critical in planning the maintenance program. Therefore, the mean work time was not used because 50 percent of the maintenance operations require more than the average work time. In this study the 85th percentile work time was considered satisfactory for scheduling the maintenance operations. The statistical method for finding the 85th percentile value of a normal distribution is:

$$P_{85} = \bar{X} + s(1.04)$$

where

P_{85} = the value of the 85th percentile,

$\bar{X}$ = sample mean, and

s = standard deviation of the sample.

The estimated work times that were used for signal head and controller maintenance were 65 min for traffic signals and 23 min for flashers. For painting the traffic signal installation the estimated work time was 175 min, and the corresponding value for flashers was 50 min. When the controller and signal head maintenance was combined with the painting operation, the expected work time was 202 min and 64 min, respectively, for traffic signal and flasher installations.

The second section of the maintenance model estimates the travel times. The relationship of travel distance and

travel time was determined for trips of various purposes. All travel resulting from the failure of a traffic signal to operate properly was considered an emergency trip. A regression analysis was performed on the data for emergency trips, and the following relationship was found:

$$Y_E = 1.352X + 7.836$$

where

Y_E = travel time in minutes, and

X = distance traveled in miles.

This regression equation, which is presented in Fig. 7 , has a coefficient of determination of 0.78.

All regular maintenance trips were classified as routine. The least-squares fit for the routine trip data resulted in the following linear equation:

$$Y_R = 1.485X + 8.542$$

where

Y_R = travel time in minutes, and

X = distance traveled in miles.

The coefficient of determination for the routine trip analysis is 0.83, and the relationship is illustrated in Fig. 7.

The curves for the emergency and routine trips were found to be similar. Therefore, the data for these trips was pooled

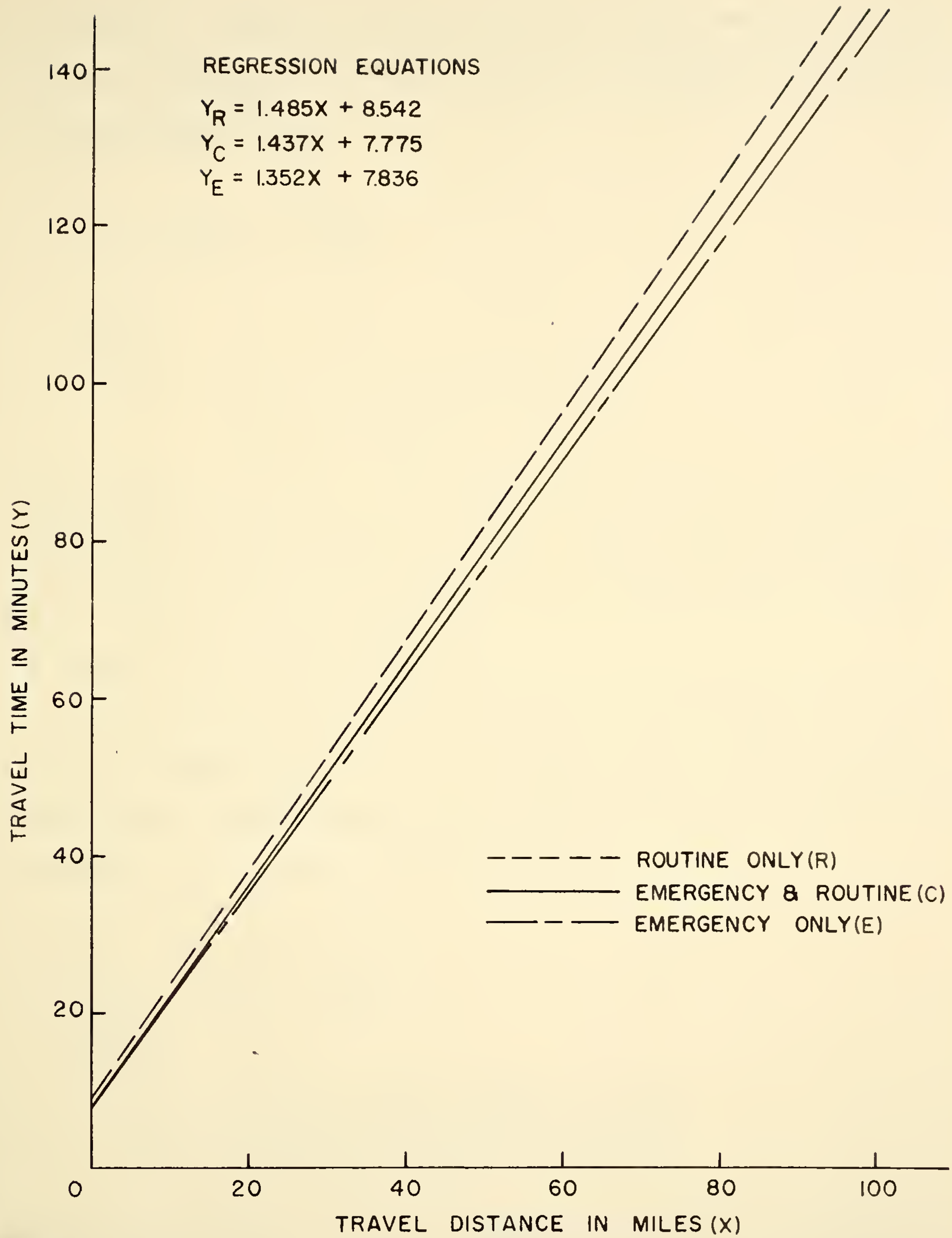


FIG. 7 REGRESSION. LINES FOR ESTIMATION OF TRAVEL TIMES FOR VARIOUS TRIP PURPOSES.

to determine a better estimate of the travel characteristics. Regression analysis of the routine and emergency data gave the following expression:

$$Y_C = 1.437X + 7.765$$

where

Y_C = travel time in minutes, and

X = distance traveled in miles.

The combined expression is illustrated in Fig. 7 , and the coefficient of correlation is 0.90. This linear equation was used to determine the emergency and routine travel times in the rest of the investigation.

The return-home trip is another travel classification. This trip originates at the last location of work and terminates at the Crawfordsville maintenance shops. The regression expression for the return-home trip is:

$$Y_{RH} = 0.802X + 36.810$$

where

Y_{RH} = travel time in minutes, and

X = distance traveled in miles.

The linear equation for the return-home trip is illustrated in Fig. 8 and has a coefficient of correlation of 0.58.

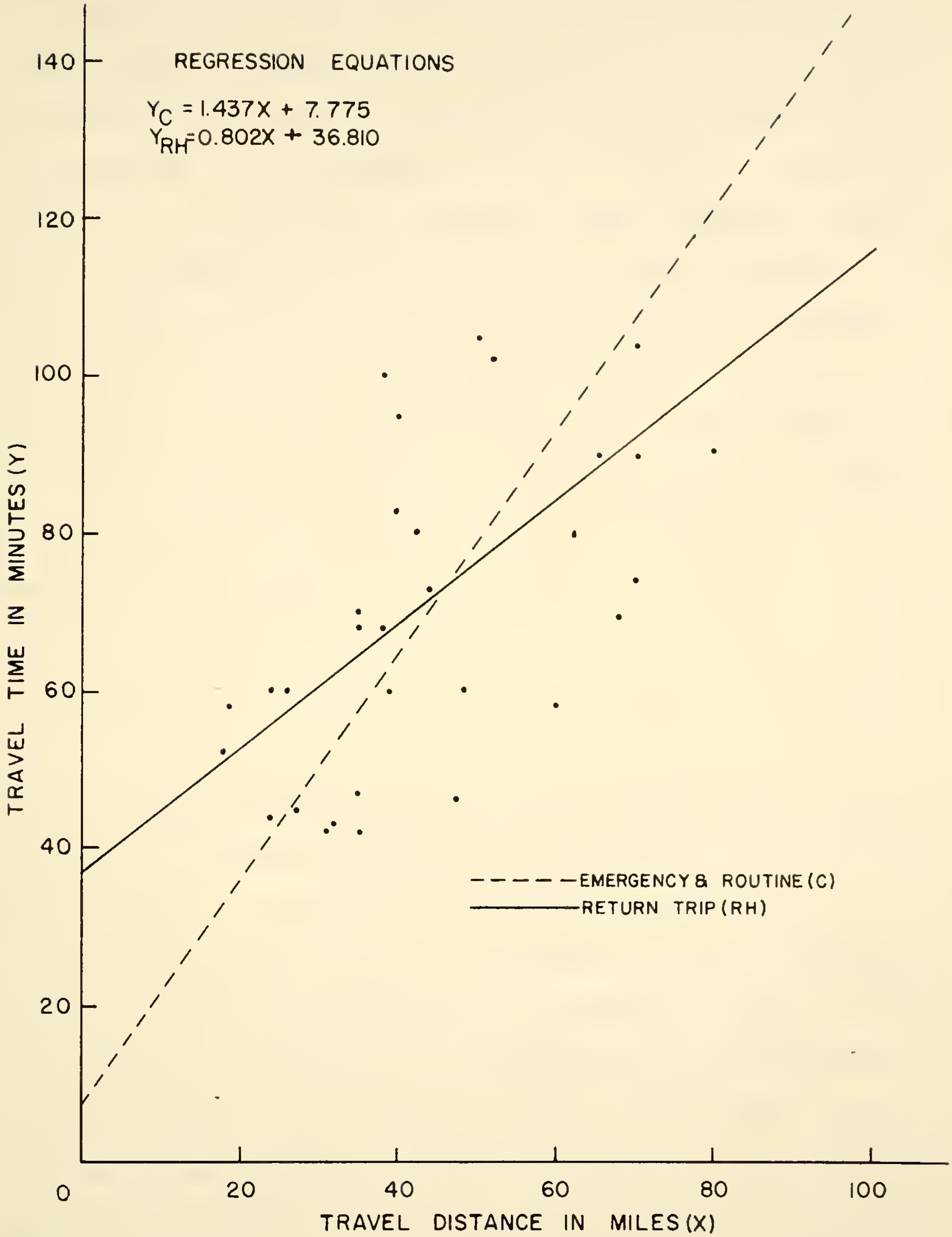


FIG. 8 REGRESSION LINE FOR THE ESTIMATION OF TRAVEL TIME FOR THE RETURN-HOME TRIP.

Because high travel times for short distances and low travel times for long distances were reported in the sample of return-home trips, this expression was not considered valid for inclusion in the development of a scientific maintenance program. A return-home trip equation which assigns time for travel commensurate with the distance traveled was desired to permit more efficient use of time available for signal and flasher maintenance. Therefore, the best available estimate of travel times was the expression determined for the pooled emergency and routine trip data, and the return-home trip times for the rest of this investigation were represented by the equation:

$$Y_C = 1.437X + 7.765$$

A plot of this expression shown by the dashed line in Fig. 7 illustrates reasonable agreement with the data collected on travel times and distances for the return-home travel.

The third section of the maintenance model involved the selection of the minimum path for a proposed routine maintenance schedule. Preparation of information for the minimum path algorithm is predicated on several conditions. The locations of all traffic signals and flashers within the study area must be known. The locations were identified, and those signals clustered in a city or town were grouped to form a node (signal node) with X signals and Y flashers. The

grouping was performed because the signals in a community were so close that any attempt to find an optimal routing within the city would produce only marginal benefits. The order of maintaining the signals within a town is left to the discretion of the work crew. However, the number of signals that are maintained in a day are specified to permit the maximum utilization of the working day. Those traffic signal and flasher locations that were isolated were considered as signal nodes with either one traffic signal or one flasher.

When the signal nodes were established, they were numbered consecutively starting with the location of the maintenance facilities as No. 1. In addition all unnumbered intersections were identified as intersection nodes, and assigned consecutive numbers that were continued from the number of the last signal node.

All directly connected nodes and lengths of the connecting links were recorded. For each pair of connected nodes there are two links, one link is from A to B and the second from B to A. The lists of links and nodes were recorded on data processing cards in accordance with the data format for the minimum path program described in Appendix B. The link and node table and the minimum path program were submitted for data processing to determine the desired minimum paths for the study area.

The output of the minimum path analysis was divided in two parts. A series of minimum path trees from each signal

node to every other node in the district was the first obtained. These trees were used to determine the shortest routes between signal nodes. Iso-lines were computed from these trees to give estimates of time and distance from nodes of interest. The minimum path tree and isotime lines emanating from Crawfordsville are graphically illustrated in Fig. 9.

The second part of the output was a matrix of the shortest distances to and from all signal nodes. This matrix was used directly as part of the data for the maintenance simulation model. A traveling salesman algorithm, using the matrix of shortest distances, considered each proposed tour and determined the best routing sequence for the signal maintenance programs that were investigated in this operational study. The first program schedules signal head and controller maintenance at six-month intervals. Painting was planned as a separate operation on a two-year schedule. The second alternative schedules signal head and controller maintenance three times in a two-year period. A fourth routine maintenance cycle in this two-year period combines painting with signal head and controller maintenance.

A number of trial solutions were made for the alternative signal maintenance programs. The procedure of testing all combinations of signals and flashers was not used because of the large number of required calculations. Optimality is not guaranteed for the maintenance alternatives because not every possible combination of traffic signals and flashers

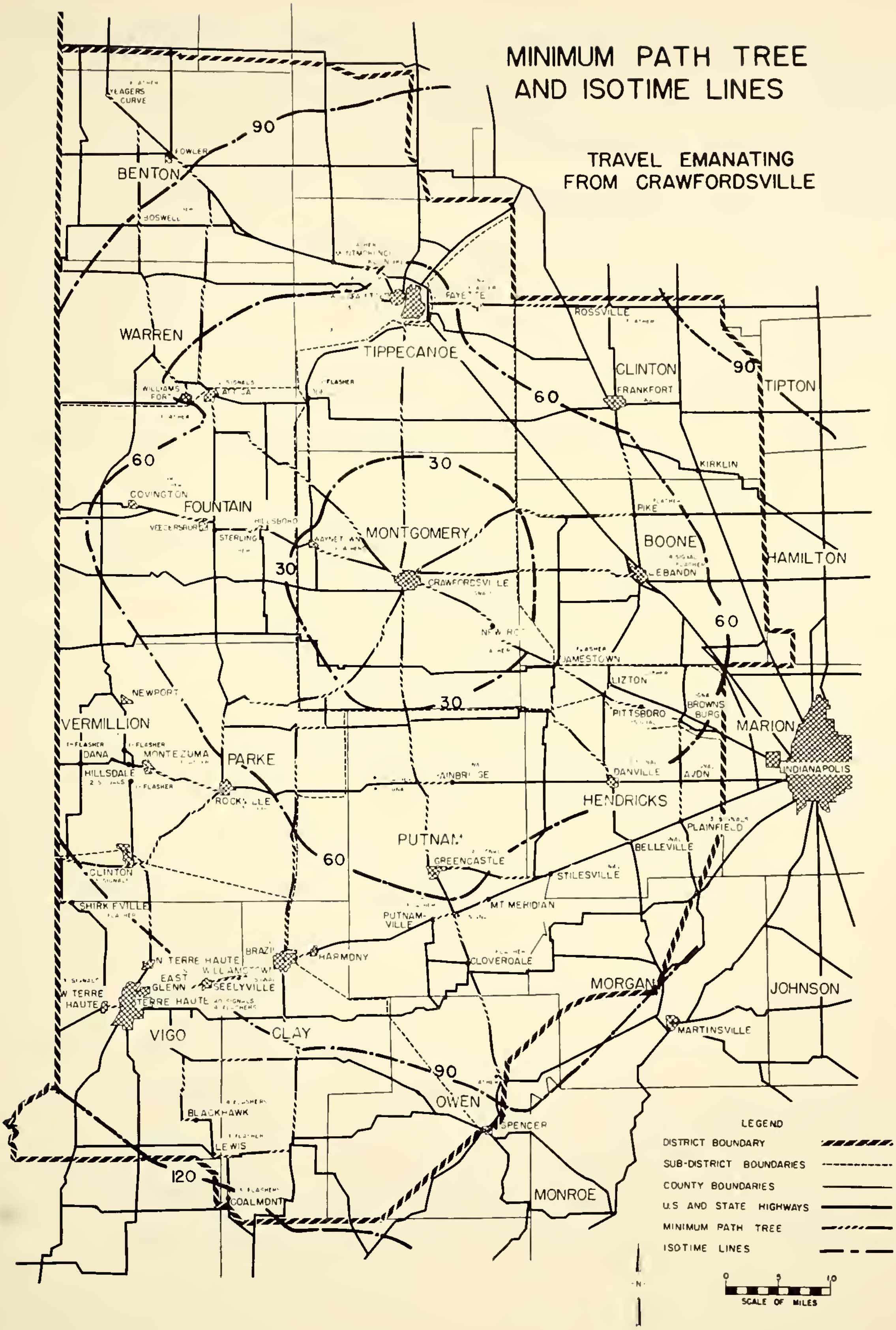

MINIMUM PATH TREE
AND ISOTIME LINES
TRAVEL EMANATING
FROM CRAWFORDSVILLE
BENTON
WARREN
TIPPECANOE
FOUNTAIN
MONTGOMERY
CLINTON
TIPTON
BOONE
HAMILTON
VERMILLION
PARKE
PUTNAM
HENDRICKS
MARION
VIGO
CLAY
MORGAN
JOHNSON
OWEN
MONROE
FOWLER
BOSWELL
YEAGERS CURVE
ROSSVILLE
FRANKFORT
KIRKLIN
PIKE
LEBANON
COVINGTON
STERLING
CRAWFORDSVILLE
JAMESTOWN
LIZTON
PITTSBORO
BROWNSBURG
INDIANAPOLIS
DANVILLE
AVON
PLAINFIELD
BELLEVILLE
STILESVILLE
GREENCASTLE
MT MERIDIAN
CLOVERDALE
MARTINSVILLE
SPENCER
HARMONY
NEWPORT
DANA
MONTEZUMA
HILLSDALE
CLINTON
SHIRKEVILLE
N TERRE HAUTE
EAST GLENN
SEELYVILLE
W TERRE HAUTE
TERRE HAUTE
BLACKHAWK
LEWIS
COALMONT
30
60
90
120
LEGEND
DISTRICT BOUNDARY
SUB-DISTRICT BOUNDARIES
COUNTY BOUNDARIES
U.S. AND STATE HIGHWAYS
MINIMUM PATH TREE
ISOTIME LINES
SCALE OF MILES
N

FIG. 9

was considered. However, the results of this testing procedure approach optimality because the minimum path tree and isotime lines emanating from Crawfordsville were used to guide the selection of groups of signal nodes for the proposed solutions of the maintenance alternatives. The groups of signal nodes, called daily tours, constituted the numbers and locations of traffic signals and flashers that were maintained in a single day for a proposed maintenance schedule. A complete maintenance schedule is composed of all the daily tours.

The proposed tours were prepared for data processing and analyzed by the maintenance simulation model on a IBM 7094. A description of this maintenance model and the information for preparing the data are presented in Appendix C.

After the computer analysis was completed, the proposed solutions were studied, and the tours were altered to more fully optimize the available work time. This process was continued until the feasible solution could no longer be changed to produce better results.

The best solution for each maintenance alternative was selected using the following criteria:

1. The work was completed in the minimum number of days,
2. The distance traveled was a minimum, and
3. Maintenance was scheduled to utilize the available time in a working day.

Then the total cost for each alternative was determined and compared on an annual-cost basis.

Contract Versus State Personnel

The annual cost of maintenance performed by state personnel and subcontractors was analyzed to determine which procedure resulted in the lowest maintenance costs. Two groups with three alternatives were tested to determine annual maintenance costs. The first group was based on current maintenance procedures, and the second policy was founded on the recommendations of the American Association of State Highway Officials.

The first alternative for each group was to assign all maintenance operations to subcontractors. The second option made the state personnel responsible for preventive maintenance and the subcontractor for corrective maintenance. The third alternative scheduled state personnel to perform the preventive and corrective maintenance operations. The analysis comparing subcontract with State maintenance was performed for Lafayette, Terre Haute, and West Lafayette.

The comparison of maintenance performed by State personnel versus contract required information regarding the times necessary to perform various maintenance operations. The previously determined work times for preventive maintenance were employed in this comparison. These work times are summarized as follows:

1. Painting.
    a. Traffic signal - 113 min.
    b. Flasher - 37 min.
2. Lamp replacement and controller maintenance.
    a. Traffic signal - 40 min.
    b. Flasher - 13 min.

Additional data were required concerning the work times necessary to restore the traffic signals and flashers to operation after the failure of some component of the signal installation. In a preceding section of the procedure, the average time required to change a lamp that has failed was found to be five minutes. The remaining failures of the traffic control installations were classified according to the source of failure - internal, minor external, and major external. Internal failures resulted from the malfunction of the signal control mechanism, and required an average repair time of 55 min for traffic signals and 23 min for flashers. Minor damage caused by external sources is another group of failures. These malfunctions are caused primarily by vandalism, power failures, and motor vehicles damaging signal heads and visors. The observed repair times for this class of failures were 21 min and 16 min for traffic signals and flashers, respectively. The final class of malfunctions, identified as major external failures, results from motor vehicles knocking down all or some part of the signal installation. The field repair times necessary to return the

traffic controls to operation averaged 120 min for signals and 57 min for flashers.

The next needed characteristic of the maintenance operation were the travel times. The expected travel times for the maintenance contractors within the three cities were determined as:

City	One-Way	Two-Way
Lafayette	6 min	12 min
Terre Haute	9 min	18 min
West Lafayette	4 min	8 min

The travel times from Crawfordsville to the cities being studied were calculated using the travel time relationship previous determined.

$$Y_C = 1.437X + 7.765$$

where

Y_C = travel time in min, and

X = distance traveled in miles

The estimated travel times from Crawfordsville are summarized as follows for the three communities that have contract arrangements:

City	Miles	One-Way	Two-Way
Lafayette	27.2	45.5 min	91 min
Terre Haute	55.6	88.5 min	175 min
West Lafayette	28.5	47.5 min	95 min

The total work times for the preventive maintenance operations were computed for each maintenance cycle. The following procedure was developed for calculating the total time required for performing the preventive maintenance by contract.

1. Assume eight hours are available per day for work.
2. Add the two-way travel time to the expected work time for the maintenance operation.
3. Multiply the number of traffic signals and flashers by their respective total work and travel times.
4. Add the times determined separately for the flashers and traffic signals to calculate the total work time.

The total times for preventive maintenance performed by sub-contractors are summarized in Table 3 . The preventive maintenance times for operations performed by the State was determined in a similar manner.

1. Assume eight hours are available per day for work.
2. Subtract the two-way travel time from the eight hours to determine the daily time available for maintenance.

TABLE 3. TOTAL TIME REQUIRED FOR VARIOUS PREVENTIVE MAINTENANCE PROGRAMS PERFORMED BY CONTRACTED AND STATE PERSONNEL

City	TOTAL TIME FOR PREVENTIVE MAINTENANCE CYCLES			
	By Contract		By State	
	Paint	Lamp and Controller	Paint	Lamp and Controller
Lafayette	42.9 hr	18.2 hr	54.6 hr	19.3 hr
Terre Haute	90.0 hr	40.8 hr	167.7 hr	46.7 hr
West Lafayette	26.2 hr	10.4 hr	35.6 hr	12.2 hr

3. Divide the expected traffic signal maintenance time into the daily time available for maintenance to determine the actual number of traffic signals that can be maintained each day without permitting the use of partial maintenance operations to completely utilize the time available for maintenance.
4. Divide the total number of traffic signals in the city by the number maintained daily to determine the days necessary to service all traffic signals.
5. Schedule flasher maintenance to complete the utilization of the work day, if such scheduling is feasible.
6. Add the work times for the remaining traffic signals and flashers that have not been previously accounted for to the two-way travel times.
7. Add the total number of days determined in step Four to the remainder time calculated in step Six to determine the total time required for preventive maintenance performed by the State.

The total times for preventive maintenance performed by State personnel are summarized in Table 3.

The field repair times were also evolved for the corrective repair operations by adding the time necessary for replacing the lamps to the various two-way travel times. The results of these calculations for the field repair times required for replacing bulbs that have failed are presented in Table 4.

TABLE 4. TIME REQUIRED TO CORRECT VARIOUS TRAFFIC SIGNAL AND FLASHER FAILURES BY CONTRACTED AND STATE PERSONNEL

City	TIME REQUIRED TO REPAIR EACH FAILURE					
	By Contract			By State		
	Lamp	Traffic Signal	Flasher	Lamp	Traffic Signal	Flasher
Lafayette	0.28 hr	1.00 hr	0.58 hr	1.60 hr	2.32 hr	1.90 hr
Terre Haute	0.38 hr	1.10 hr	0.68 hr	3.00 hr	3.71 hr	3.30 hr
West Lafayette	0.22 hr	0.93 hr	0.52 hr	1.67 hr	2.38 hr	1.97 hr

The analysis of traffic signal and flasher failures for internal, external minor, and external major classifications resulted in a situation where no conclusive results could be related to the failures. Therefore, a composite of the three signal failure types for Lafayette, Terre Haute, West Lafayette, and the remainder of the district was used to determine the patterns of signal malfunctions. The following weighted means were computed for the combined failures.

Failures	Signals		Flashers	
	Avg. Time	Percent Observed	Avg. Time	Percent Observed
Internal	55 min	55	23 min	61
External				
Minor	21 min	36	16 min	32
Major	120 min	9	57 min	7
Composite Average	48.3 min	100	23.2 min	100

The total field repair times were calculated by adding the composite repair times to the corresponding two-way travel times. These findings are summarized in Table 4.

The rates for the various classes of failures were necessary in the comparison of preventive and emergency maintenance performed by the State of subcontractor. The lamp failure rates for the existing conditions were obtained by observing the number of failures that occurred in each situation during the 268 days of data collection. The probabilities for the lamp failures are summarized as follows:

1. Lafayette - 0.196 failures per day,

2. Terre Haute - 0.308 failure per day,

3. West Lafayette - 0.018 failures per day, and

4. Remainder of district - 0.045 failures per day.

The total number of lamp failures that were recorded annually for the existing maintenance policies are presented in Table 5.

Lamp failures were determined for the lamp replacement program that has been adopted by the Indiana State Highway Commission. Currently, the State uses 6000-hr lamps and schedules group lamp replacement every 12 months. The number of expected failures were determined by using the lamp mortality curve, illustrated in Fig. 6 , the lamp burning times presented in Table 2 , and the observed numbers of lamps in Lafayette, Terre Haute, and West Lafayette shown in Table 6. For the given period of replacement time, the percentage of rated life consumed is determined by dividing the hours burned by the replacement time interval. The estimated percentage of lamps surviving at the end of the replacement period is then determined from the morality curve. The expected annual numbers of lamp failures for Lafayette, Terre Haute, and West Lafayette are illustrated in Table 5 for the current State lamp replacement program.

The same method described above was used to determine the expected number of lamp failures for the A.A.S.H.O. replacement policy. The American Association of State Highway

TABLE 5. ACTUAL AND EXPECTED LAMP FAILURES

City	Actual Lamp Failures	Expected Lamp Failures for Various Preventive Maintenance Policies	
		Indiana	AASHO
Lafayette	72	18	4
Terre Haute	113	35	9
West Lafayette	7	10	2

TABLE 6. OBSERVED NUMBER OF SIGNAL LAMPS USED IN VARIOUS CITIES

USE	CITIES		
	Lafayette	Terre Haute	West Lafayette
Traffic Signals	489	1059	326
Flashers	26	17	0
TOTAL	515	1076	326

Officials recommends group lamp replacement every six months.(21) This analysis was also based on a rated lamp life of 6000 hr because these lamp types were most commonly used in the study maintenance district. A summary of expected lamp failures for the A.A.S.H.O. policy, the actual failures, and those expected for the State replacement program are compared in Table 5.

The composite failure rates for traffic signals were analyzed with the Chi-square test, and it was determined that the failure patterns were reasonably approximated by the Poisson distribution at the five percent level with 13 degrees of freedom. For the remainder of this study the traffic signal failure rate was assumed as a Poisson distribution with a mean of 0.0063 failures per day per signal. The annual number of signal failures was determined by multiplying the rate times the number of days per year and the number of traffic signals in each city. The number of traffic signal failures are summarized in Table 7.

The composite failure rate for flashers was found to be 0.002 failures per day per flasher. The annual number of flasher failures for Lafayette, Terre Haute, and West Lafayette were calculated in a similar manner and are shown in Table 7.

The hours required annually for corrective maintenance in Terre Haute, Lafayette, and West Lafayette were calculated for each maintenance alternative. The procedure for calculating

TABLE 7. ACTUAL FAILURES FOR TRAFFIC SIGNALS AND FLASHERS DUE TO LAMPS, INTERNAL, AND EXTERNAL CAUSES

City	Lamp	Traffic Signals	Flashers
Lafayette	72	46	1
Terre Haute	113	92	3
West Lafayette	7	30	0

the annual corrective work time is presented in the following outline.

1. Multiply the annual number of lamp failures by the field lamp replacement time.
2. Multiply the yearly number of traffic signal failures by the field time necessary to repair a traffic signal malfunction.
3. Multiply the annual number of flasher failures by the field time required to correct the flasher failure.
4. Add steps one, two, and three to determine the total annual corrective time.

The annual work times for corrective maintenance are summarized in Table 8.

The annual times devoted to preventive maintenance were determined by applying the proper work times to the maintenance programs summarized below.

Maintenance Programs	Lafayette	Terre Haute	West Lafayette
Existing Policy			
Lamp	All in face when one fails	None	Once every 12 months (State)
Controller	None	None	Once every 12 months (State)
Paint	None	None	Once every 4 years (State)

TABLE 8. ANNUAL CORRECTIVE MAINTENANCE TIMES CONTRACT AND STATE PERSONNEL FOR VARIOUS MAINTENANCE PROGRAMS

CITIES	MAINTENANCE PERFORMED BY CONTRACT			MAINTENANCE PERFORMED BY STATE PERSONNEL	
	Existing Program	Indiana Program	AASHO Program	Indiana Program	AASHO Program
Lafayette	66.8 hr	56.6 hr	47.7 hr	132.7 hr	110.3 hr
Terre Haute	144.0 hr	123.3 hr	104.4 hr	455.9 hr	377.9 hr
West Lafayette	29.4 hr	30.1 hr	28.3 hr	88.1 hr	74.6 hr

Indiana	Change all lamps every 12 months and at the same time service the controller. Every four years paint the signal installation.
A.A.S.H.O.	Change all lamps and service the controller every six months. Paint the signal installation every two years.

The summary of annual preventive work times is shown in Table 9.

The costs of men and equipment used for maintenance operations were determined from information supplied by the Indiana State Highway Commission. The typical maintenance crew for the State consists of two men at $2.45 per hour and one truck at $5.00 per hour. The total cost of men and equipment is $9.90 per hour for the State operation. The hourly maintenance costs for Lafayette and West Lafayette were determined by allocating one electrician at $2.53 per hour, and one helper at $1.88 per hour, and one truck at $1.00 per hour for each maintenance operation. Therefore, the hourly maintenance cost for Lafayette and West Lafayette was determined as $5.41 per hour.

An anomaly was observed for Terre Haute because the present maintenance costs are assessed at a flat rate of $2.00 per month per signal installation. The total annual cost of this procedure amounts to $960.00. However, when comparing the costs of State versus contract maintenance the hourly maintenance costs were assumed equal to those in Lafayette and West Lafayette.

TABLE 9. ANNUAL PREVENTIVE MAINTENANCE PERFORMED BY CONTRACT AND STATE PERSONNEL FOR VARIOUS MAINTENANCE PROGRAMS

MAINTENANCE PROGRAMS	CITIES		
	Lafayette	Terre Haute	West Lafayette
Existing Policy			
Subcontract	12.0 hr	0.0 hr	21.1 hr*
State Personnel	33.0 hr	88.6 hr	21.1 hr
A.A.S.H.O. Policy			
Subcontract	57.8 hr	125.8 hr	33.9 hr
State	65.9 hr	174.2 hr	42.2 hr

*Preventive Maintenance Performed by State

The total annual preventive and corrective maintenance field costs were calculated by applying the lamp cost and hourly wage and equipment charges to the data for the maintenance alternatives illustrated in Tables 9 and 9 . The annual field maintenance costs are illustrated in Table 10 . A cursory inspection of the table reveals that the annual cost of maintenance performed by subcontractors is less than the cost of maintenance performed by State personnel because the hourly maintenance costs for the State are almost twice those for the contractor. In addition, the travel time for the State forces to the site of the maintenance operation is about ten times longer than the travel time for the various contractors.

A direct comparison of the annual costs for the existing conditions and the A.A.S.H.O. policy is not valid. These alternatives should be compared in a manner consistent with the importance placed on dependable signal operation. However, it was not the purpose of this section to make a comparison of the two traffic signal maintenance programs. The two alternatives were presented to illustrate that there is a general pattern of annual costs for maintenance performed by the State personnel and subcontractors.

TABLE 10. TOTAL ANNUAL FIELD COSTS FOR VARIOUS MAINTENANCE ALTERNATIVES

MAINTENANCE PROGRAM	CITIES		
	Lafayette	Terre Haute	West Lafayette
Existing Policy			
Subcontract	$ 460.50	$ 960.00	$ 422.25
Subcontract and State	$ 691.40	$1,716.50	$ 422.75
State	$1,722.40	$5,574.00	$1,134.25
A.A.S.H.O. Policy			
Subcontract	$ 736.50	$1,592.50	$ 441.20
Subcontract and State	$1,075.50	$2,635.50	$ 675.00
State	$1,555.50	$5,809.50	$1,261.00

Staffing

A vital part of a comprehensive signal maintenance program involves the determination of the staff necessary to insure proper signal operation. The optimal lamp replacement periods and maintenance sequencing can be determined, but if there is an insufficient maintenance staff, the proposed maintenance program is not utilized for the full benefit of the maintenance agencies.

The staffing was determined for that part of the Crawfordsville maintenance district which is maintained by State personnel. Lafayette, Terre Haute, and West Lafayette were not considered because the signal maintenance is more economically performed in these cities by subcontract. Delimiting the maintenance responsibilities in this manner made it reasonable to assume that traffic signals and flashers are uniformly distribtuted throughout the portion of the maintenance district being considered. The previously calculated average distances of signal installations from Crawfordsville were used to estimate the travel distances for the corrective operations. The mean distance from Crawfordsville for traffic signals was 30.66 miles, and for flashers the average distance was 36.26 miles.

The travel times for the corrective maintenance operations were estimated by the combined travel times expression:

$$Y_C = 1.437X + 7.765$$

where

Y_C = travel time in min, and

X = distance traveled in miles.

The average times required for travel to the site of a failure were 52.7 min for traffic signals and 60.1 min for flashers. Two-way travel times were used in this investigation for two reasons. First, the travel to and from the failure site is part of the total time required for the corrective maintenance operation. Second, when two failures are rectified without returning to Crawfordsville between the operations, the total travel time was estimated by two round trips. The validity of using two round trips is illustrated by considering Crawfordsville to be located centrally within the maintenance district. The remaining signal locations in the district have greater average distances to the other signal locations. Therefore, the three links for a tour starting at Crawfordsville and proceeding to two consecutive failure sites and returning to Crawfordsville is, on the average, longer than a tour whose total distance is estimated by three one-way links determined from the central location. The four one-way trips will exceed the average three link tour, but in keeping with the conservative estimates used in this study the use of two two-way travel time was considered appropriate. Therefore, the round-trip travel times assigned for the

traffic signal and flasher repair operations were 105.4 min and 120.2 min, respectively.

The total field times required to perform the repair operations were necessary in analyzing the staffing problem. The work times for repairing the traffic signals and flashers were 48.3 min and 23.2 min, respectively, and the total field times for the repair operations were 153.7 min for traffic signals and 143.4 min for flashers. In addition, the average field time for changing a lamp that has failed was previously calculated as 110 min.

The daily rate of traffic signal failures for the Crawfordsville maintenance district was determined to be approximated by a Poisson distribution with a mean of 0.0063 failures per day per signal. The 57 signals considered in the staffing problem have a failure rate of 0.359 failures per day. The expected daily traffic signal failure probabilities illustrated in Table 11 were calculated by computational procedures commonly used for Poisson expressions.

An anomally was observed in determining the failure pattern for flashers. All flasher failures were observed in the period starting the first of July and ending the first of October. An extensive reappraisal of the data and the collection methods revealed that the source of the inconsistency was not in the method used to report the daily traffic signal and flasher maintenance activity. Because an estimate

TABLE 11. PROBABILITY OF THE NUMBER OF EXPECTED FAILURES PER DAY FOR VARIOUS MALFUNCTIONS

Failure	Probability of the Number of Expected Failure per Day				
	0	1	2	3	4
Traffic Signal	0.698	0.251	0.045	0.006	-----
Flasher	0.834	0.122	0.044	-----	-----
Lamps	0.964	0.036	-----	-----	-----
Traffic Signals, Flashers and Lamps	0.559	0.302	0.114	0.023	0.002
Traffic Signals and Lamps	0.673	0.267	0.052	0.008	-----

pertaining to the number of flasher failures was necessary for determining the number of days not available for preventive maintenance, it was deemed satisfactory to use the observed pattern of failures for a 90 day period and assume there would be no failures during the remaining 275 days of the year. The observed flasher failure probabilities observed for this time interval are shown in Table 11.

The probability of lamp failure was computed by analyzing the data for existing conditions. A total of 17 lamp failures was observed to be dispersed randomly throughout the year. The resulting failure pattern distribution is illustrated in Table 11.

The summation of traffic signal, flasher, and lamp failure probabilities were calculated by estimating the probabilities of every possible combination of failure. The results of the failure calculations are illustrated in Table 11. In a similar manner the failure probabilities were obtained for the situation when flasher failures are not expected, and the results of these calculations are also summarized in Table 11.

A weighted mean representing the daily average repair time was determined by using the failure probabilities shown in Table 11 and the expected field repair times of 153.7 min for traffic signals, 143.4 min for flashers, and 110 min for lamps. The results of these calculations are tabulated as follows:

Daily Average Repair Times

Traffic signals, Flashers, and Signal Lamps	85.9 min
Traffic Signals and Signal Lamps	58.8 min

The staff required to correct the expected signal failures could be determined by an economic analysis if a failure penalty were determined. However, no penalty was assessed because of the difficulty in assigning realistic costs for accidents and delays caused by signal failures. The staff required to satisfactorily perform the necessary maintenance operations was determined by considering the following factors:

1. The failure probabilities expressed in Table 11.
2. The average daily repair times,
3. The anticipated time required to perform the preventive maintenance operations, and
4. The suitability of certain seasons for preventive maintenance operations.

The total time available for the preventive maintenance operations was calculated and a decision was made concerning the staff required to perform the maintenance operations in the time allocated to preventive maintenance operations.

RESULTS

The results of this investigation of the traffic signal and flasher maintenance for the Crawfordsville district are presented in this section of the report. All phases of the corrective and preventive maintenance operations were analyzed to determine the optimal maintenance program. The optimum lamp replacement program, involving the determination of the proper time intervals for scheduling group lamp replacements and the most economic lamp life, was ascertained from the results of the lamp replacement model. The shortest route for preventive maintenance operations was determined for several maintenance alternatives, and by comparing the anticipated annual costs, the most economic option was revealed. An economic analysis was performed to compare the maintenance costs for work executed by State personnel and by subcontractors. Recommendations were made concerning the advisability of allocating additional maintenance responsibilities to contractors. The staff necessary for effective traffic signal and flasher operation was obtained from the results of the lamp replacement model, the maintenance simulation model, and the comparison of maintenance performed by State personnel and contractor.

Lamp Replacement

The lamp replacement model was designed to produce results applicable to both the general lamp replacement problem and the observed conditions for the Crawfordsville maintenance district. The optimal lamp replacement periods were determined for various ratios of replacement costs (group replacement versus replacement at failure). The optimal lamp replacement times were analyzed by regression methods to determine a curve that accurately estimates the observed conditions. The optimum lamp replacement intervals were best predicted by the following relationship:

$$Y = 32.82 + 1.54X - 0.31 \times 10^{-1}X^2 + 0.31 \times 10^{-3}X^3 - 0.11 \times 10^{-5}X^4$$

where

Y = (the ratio of optimum replacement time to rated lamp life) x 100, and

X = (the ratio of group replacement cost to replacement cost at failure) x 100.

The regression curve, illustrated in Fig. 10 is a good estimator of observed conditions because the standard error of estimate was only 1.10 percent about the regression curve. The fifth-power term was not included in the expression because it contributed insignificantly to fitting the curve to the data. However, the fourth-power term is highly significant in this regression analysis.

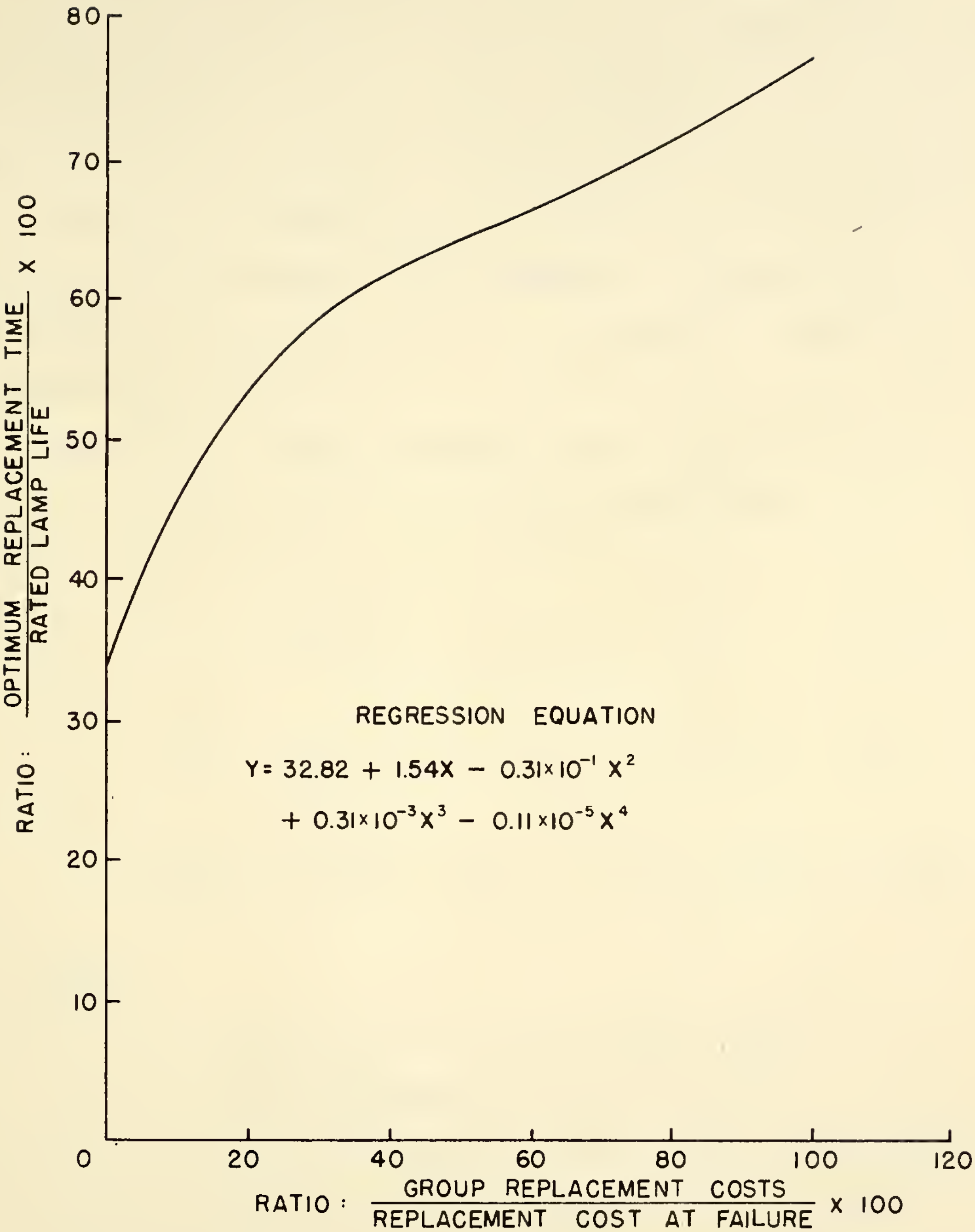


FIG. 10 REGRESSION LINE FOR ESTIMATING THE OPTIMUM LAMP REPLACEMENT TIME.

The relationship expressing the optimum replacement period as a function of the ratio of replacement costs can be used to determine the best group replacement time for lamps used in traffic signals and flashers. The general usage of this function is restrained by the manner in which the lamp failures are corrected. The assumption concerning lamp failures used in this analysis is that lamps are immediately replaced upon failure.

Annual cost calculations were performed for various rated lamp lives using the following replacement model:

$$X_t = (c/t) + \Big[k(P(T_1 < t) - P(T_1 + T_2 < t)) + 2k(P(T_1 + T_2 < t) - P(T_1 + T_2 + T_3 < t)) + \ldots + nk(P(T_1 + T_2 + \ldots + T_n < t) - P(T_1 + T_2 + \ldots + T_n + T_{n+1} < t)) \Big] (1/t)$$

where

X_t = cost per hr of operation per lamp,

t = lamp replacement period in hours,

c = cost of replacing a lamp in group replacement,

k = cost of replacing a lamp at failure, and

T_i = lamp life in hours of the ith lamp when $T \sim N(100,25)$ where the lamp lives are independent.

The longer rated lamp lives had lower annual maintenance costs. The following example demonstrates the validity of the observed results concerning annual maintenance costs.

1. Compare two lamps where lamp A has twice the rated life of lamp B.
2. Change all lamps at 50 percent of the rated lamp life.

If the costs per replacement cycle for lamps A and B are equal, a valid comparison of the maintenance costs is obtained by prorating the maintenance costs for each lamp type over a given unit of time. Therefore, the maintenance costs using lamp B are twice those of lamp A, because bulb B requires two maintenance cycles for every cycle for bulb A.

If the maintenance policy is set at a fixed replacement interval, then the results are similar to those noted in the previous case. For this situation the group replacement costs are equal for lamps A and B because the same number of replacement are scheduled for each time interval. The difference in maintenance costs originates from the number of expected lamp failures for these two types of bulbs. Fewer bulb failures develop for the longer rated life than for the shorter lamp life. Therefore, the total costs of the maintenance cycles are less then lamps of longer rated lives are used, but lamps with shorter rated lives are more economically used when the anticipated burning times are very short. This stipulation is based on the fact that the anticipated savings in lamp

failure costs resulting from using longer life lamps do not offset high bulb purchase prices.

The analysis of the maintenance conditions was performed for several lamp replacement alternatives. Two rated lamp lives of 6000 and 8000 hr were considered in this analysis. The 8000-hr lamp was studied because it had the longest rated lamp life that concurred with the voltage and wattage requirements of the study district. The 6000-hr lamp was included in the analysis because the 8000-hr lamp was not acceptable by A.A.S.H.O. standards. The lamp in question was rated at 575 lumens, and the American Association of State Highway Officials indicates that 665 lumens are necessary for 8000-hr bulbs. (1)

These lamps (6000 and 8000 hr) were applied to several group replacement programs. The first lamp replacement alternative closely approximates replacing the individual lamps used in traffic signals (red, green, and amber) and flashers at the optimum intervals determined by the curve illustrated in Fig. 10. Analysis of this replacement option necessitates the reappraisal of the group replacement costs which were established in the procedure for estimating the total cost of replacing all lamps in the same preventive maintenance cycle. Certain elements of the group replacement program, travel time and controller maintenance, are performed regardless of the number of lamps replaced at a signal location. Because the optimal replacement period for lamps used

in flashers and the red position in traffic signals was approximately the same, the total travel time for the best route sequence was used for every maintenance cycle. However, the computations were performed by distributing the total travel time in proportion to the number of traffic signals and flashers in the study district.

The maintenance time for changing lamps and controller maintenance was allocated in a manner consistent with the anticipated work for each maintenance cycle. The maintenance time for flashers were unchanged because the complete maintenance operation was performed for each scheduled cycle. The traffic signal required allocations of maintenance times because all the lamps are not scheduled for replacement in each preventive cycle. Controller maintenance was allotted 55 percent of the work time, and 15 percent was allocated to each lamp use changed (red, green, and amber). Therefore, the times required for each traffic signal operation were computed by adding the controller maintenance times to the total for the lamp uses replaced.

The total costs for the preventive maintenance operation were calculated by adding the proper travel times to the anticipated work times, and this sum was multiplied by the hourly cost of men and equipment ($9.90 per hour) for maintenance performed by State personnel. These computations are tabulated as follows:

Use	Number of Lamps	Group Replacement Cost	Cost per Lamp	Percent Rated Life
Flashers	170	$ 404.00	$2.38	48
Traffic Signals				
One Lamp	513	$ 567.25	$1.10	42
Two Lamps	1,026	$ 822.50	$0.83	41
Three Lamps	1,539	$1,158.75	$0.76	40

The technique for determining the optimum replacement schedule and the annual cost of this policy are summarized below.

1. Determine the ratio of group replacement costs to replacement costs at failure (Fig. 10) for the Crawfordsville maintenance district.
2. Apply the replacement cost ratio to the optimum replacement curve to determine the percentage of rated life for the replacement period.
3. Use the optimum percentages of rated life to determine the number of hours the lamps should be permitted to burn before replacement.
4. Use Table 2 and the optimum burning times to calculate the replacement intervals for lamps used in flashers and traffic signals. These calculations were rounded to the nearest six months to facilitate consolidating the independent lamp replacement cycles.
5. Apply the expected lamp burning times to the replacement model to calculate the anticipated annual costs.

The results of these annual cost calculations for the optimum lamp replacement program are summarized in Table 12.

Two additional lamp replacement programs were considered in this investigation. The first program schedules lamp replacement every 12 months, and the second alternative plans group replacement for six-month intervals. The annual costs of these maintenance programs were determined by applying the group and failure costs determined in the procedure to the lamp replacement model, and the results are presented in Table 13.

The results of the computations summarized in Tables 12 and 13 reveal several significant facts. The 8000-hr lamp is designated as the optimum lamp for use in the Crawfordsville maintenance district if the criteria for judgement are economic considerations. In addition, the lamps used in flashers and those used in the red and green positions of traffic signals should be changed every 12 months. The bulbs used for the amber indication in traffic signals need only be replaced every four years. However, if the lamps used in the amber position are changed each year the annual cost is increased by 0.42 percent.

The best lamp replacement program for the 6000-hr lamp is considered because the 8000-hr lamp does not meet A.A.S.H.O. specifications. The lamps used in the red and green positions of traffic signals and those used in flashers should be replaced at six-month intervals. The lamps used in the amber

TABLE 12. ANNUAL COST OF OPTIMUM REPLACEMENT PROGRAM USING SEVERAL RATED LAMP LIVES

Lamp Use	8000 HR LAMP		6000 HR LAMP	
	Lamp Change Interval	Cost Per Year	Lamp Change Interval	Cost Per Year
Flasher	1.0 yr	$ 777.70	0.5 yr	$ 914.20
Traffic Signal				
Red	1.0 yr	$ 948.38	0.5 yr	$ 983.16
Green	1.0 yr	$ 637.38	0.5 yr	$ 989.06
Amber	4.0 yr	$ 109.13	3.5 yr	$ 149.60
Total Annual Cost		$2,472.59		$2,945.02

TABLE 13. ANNUAL COST OF SEVERAL FIXED TIME INTERVAL LAMP REPLACEMENT PROGRAMS

	REPLACEMENT PROGRAMS			
Lamp Use	Change Lamps at 6 Month Intervals		Change Lamps at 12 Month Intervals	
	6000 Hr Lamp	8000 Hr Lamp	6000 Hr Lamp	8000 Hr Lamp
Flasher	$ 392.20	$ 307.10	$1,440.50	$ 516.70
Traffic Signal				
Red	$ 996.50	$ 893.26	$2,422.00	$ 979.13
Green	$ 911.40	$ 878.16	$1,380.00	$ 667.13
Amber	$ 833.70	$ 843.21	$ 418.36	$ 422.13
Total Annual Cost	$3,133.80	$2,921.73	$5,660.86	$2,585.04

indication are most economically replaced every 42 months. The annual cost of the group replacement program is increased 6.38 percent by scheduling the amber replacements every six months.

The determination of the optimal lamp replacement policy involves more than economic considerations alone. The following factors must be considered, and their importance must be carefully weighed with respect to the final results on the system of traffic control:

1. As the period between lamp replacements increase, the number of expected failures becomes greater.
2. Fewer failures are expected per unit of time for a lamp with a longer rated life.
3. Hazards to the motorist increase as the number of signal failures increase.
4. With longer burning times, less light is emitted because of the condensation of filament vapors on the lamp envelope. (41)
5. Less light is emitted with increasing time between the cleaning of the optical units.
6. As less light is emitted from the signal, the potential hazard to the motoring public becomes more pronounced. This factor is critical for the red position because it indicates the stop condition and eye sensitivity is lower in that portion of the spectrum. (41)

The use of the optimum replacement curve, economic considerations, and the above mentioned factors results in a group lamp replacement policy that is in perspective with the goals of traffic signal and flasher operation.

Optimal Route Sequencing for Preventive Maintenance

This portion of the maintenance problem was concerned with the optimal scheduling and sequencing of routine preventive maintenance operations. The model analysis was separated into three parts to consider several possible preventive maintenance alternatives. The first section develops the optimal routing for preventive operations concerned only with signal lamp and controller maintenance. Then, the shortest sequence of signal nodes was developed for the painting operation. The last phase necessitated the selection of the shortest route for scheduling signal lamp, controller, and painting maintenance. The results of the model analysis for the three preventive maintenance operations are summarized in Tables 14, 15 , and 16 , respectively. The best group of tours for each maintenance alternative was selected using the following criteria:

1. The work was completed in the minimum number of days,
2. The distance traveled was a minimum, and

TABLE 14. SUMMARY OF RESULTS OF MODEL ANALYSIS FOR CHANGING LAMPS AND CONTROLLER MAINTENANCE FOR TRAFFIC SIGNAL AND FLASHER INSTALLATIONS

		SET					
		1	2	3	4	5	6
Total Distance in Miles		1522.00	1522.60	1507.60	1597.00	1519.90	1606.30
		NUMBER OF DAYS					
		17	17	17	17	17	17
Total Number of Hours Worked							
Less Than	Greater Than						
	8:30	0	0	0	0	0	0
8:30	8:10	0	0	0	0	0	0
8:10	8:05	0	1	1	0	0	0
8:05	7:45	10	7	10	12	9	11
7:45	7:30	4	5	1	3	4	4
7:30	7:00	2	3	2	1	3	1
7:00	6:00	0	0	3	0	0	1
6:00		1	1	0	1	1	0

TABLE 15. SUMMARY OF RESULTS OF MODEL ANALYSIS FOR PAINTING TRAFFIC SIGNAL AND FLASHER INSTALLATIONS

		SET						
		1	2	3	4	5	6	7
Total Distance in Miles		3879.5	3523.6	3773.5	3422.0	3451.3	3378.4	3424.9
		NUMBER OF DAYS						
		47	46	46	42	41	41	41
Total Number of Hours Worked								
Less Than	Greater Than							
	8:30	0	0	0	0	1	0	0
8:30	8:10	0	0	0	1	3	0	0
8:10	8:05	0	0	0	1	0	3	3
8:05	7:45	4	3	7	30	36	34	36
7:45	7:30	8	4	7	6	0	3	0
7:30	7:00	21	23	18	2	0	0	1
7:00	6:00	10	15	13	1	0	0	1
6:00		4	1	1	1	1	1	0

TABLE 16. SUMMARY OF RESULTS OF MODEL ANALYSIS FOR CHANGING LAMPS, CONTROLLER MAINTENANCE, AND PAINTING TRAFFIC SIGNAL AND FLASHER INSTALLATIONS

		SET 1	SET 2	SET 3	SET 4	SET 5
Total Distance in Miles		4269.1	4244.8	4152.4	4146.5	4131.2
		NUMBER OF DAYS				
		53	53	51	51	51
Total Number of Hours Worked: Less Than	Greater Than					
	8:30	0	0	0	0	0
8:30	8:10	2	0	5	2	0
8:10	8:05	1	2	2	3	5
8:05	7:45	36	38	40	45	44
7:45	7:30	8	8	2	0	1
7:30	7:00	4	3	2	0	0
7:00	6:00	0	1	0	0	0
6:00		2	1	0	1	1

3. Maintenance was scheduled to utilize the available time in a working day.

The optimal selection for changing the lamps and for controller maintenance is Set 5, in which the total time required to perform the maintenance operation is 121 hr and 52 min. Set 6 is the best routing for painting the traffic signal and flasher installations. The option requires 322 hr and 3 min to complete the maintenance cycle. Set 5 which requires 405 hr and 8 min per cycle is the optimum schedule for combining changing the lamps and controller maintenance with the painting operation.

The three optimum maintenance sets were combined in accordance with A.A.S.H.O. preventive maintenance specifications. The American Association of State Highway Officials recommends that lamps and controllers be maintained every six months, and that the traffic signal and flasher installations be painted at two-year intervals.(21) Two maintenance alternatives result from the A.A.S.H.O. policy. One class schedules signal head and controller maintenance at six-month intervals while painting is planned as a separate operation on a two-year schedule. The other alternative requires that signal head and controller maintenance be performed three times in a two-year period. A fourth maintenance cycle in this two-year interval combines painting with signal head and controller maintenance. Annual costs were calculated for the

two alternatives by multiplying the anticipated hours required annually for each option by the hourly costs of men and equipment previously determined in the procedure for maintenance performed by State personnel. The results of these computations are presented in Table 17.

The annual cost of alternative two is slightly less expensive than alternative one. However, alternative one is not recommended because it lacks sufficient flexibility for use in a system where failures occur randomly and where good weather cannot be guaranteed for proper painting and preventive maintenance conditions. When the painting operations are scheduled separately from the lamp and controller maintenance, the time required for painting can reduce the slack time in the work load if weather conditions are satisfactory. The painting operation can be used during these slack periods because the continued and accurate operation of the traffic control device is not critically dependent on this phase of maintenance. However, when the painting and the signal head and controller maintenance operations are combined, the painting operation becomes critical because the dependable operation of the traffic control devices is directly related to the lamp and controller maintenance. Therefore, the optimal sequencings of the more flexible first alternative are presented in Table 18 for the routine lamp and controller maintenance and in Table 19 for the painting operation.

TABLE 17. ANNUAL COST OF VARIOUS PREVENTIVE MAINTENANCE ALTERNATIVES

Alternative One	
4 Lamp Changes @ 121.82 hr per cycle	= 487.28 hr
1 PaintOnly @ 322.05 hr per cycle	= 322.05 hr
Total Hours in 2 yr Period Devoted to Preventive Maintenance	= 809.33 hr
Total Hours in 1 yr Period Devoted to Preventive Maintenance	= 404.66 hr
Total Annual Preventive Maintenance Cost @ $9.90 per hr	= $4,000.00
Alternative Two	
3 Lamp Changes at 121.82 hr per cycle	= 365.46 hr
1 Lamp Change and Paint Combined @ 406.13 hr per cycle	= 406.13 hr
Total Hours in 2 yr Period Devoted to Preventive Maintenance	= 771.59 hr
Total Hours in 1 yr Period Devoted to Preventive Maintenance	= 385.80 hr
Total Annual Preventive Maintenance Cost @ $9.90 per hr	= $3,820.00

TABLE 18. OPTIMAL SEQUENCE OF TRAFFIC SIGNALS AND FLASHERS FOR LAMP AND CONTROLLER MAINTENANCE

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
1	5.00	1.00	Brazil	Clay
2	---	1.00	Williamstown	Clay
2	5.00	---	Brazil	Clay
3	1.00	---	East Glenn	Vigo
3	1.00	---	Seelyville	Vigo
3	2.00	---	Brazil	Clay
3	1.00	---	US-40; SR-43	Putnam
4	---	3.00	Blackhawk	Vigo
4	3.00	---	West Terre Haute	Vigo
5	---	1.00	Cloverdale	Putnam
5	---	1.00	US-231; SR-67	Owen
5	---	3.00	Coalmont	Clay
5	---	4.00	Lewis	Vigo
5	---	1.00	Blackhawk	Vigo
6	3.00	---	Clinton	Vigo
6	---	1.00	Shirkieville	Vigo
6	---	1.00	US-36; SR-71	Vermillion
6	---	1.00	US-36; SR-63	Vermillion
7	4.00	---	Greencastle	Putnam
7	1.00	1.00	Putnamville	Putnam

TABLE 18. (continued)

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
8	3.00	---	Rockville	Parke
8	---	1.00	US-35; SR-43	Putnam
8	1.00	---	Bainbridge	Putnam
8	1.00	---	US-36; SR-43	Putnam
9	---	1.00	Montezuma	Vermillion
9	1.00	---	Hillsdale	Vermillion
9	---	1.00	US-36; SR-63	Vermillion
9	1.00	2.00	Covington	Fountain
9	---	2.00	Sterling	Fountain
9	---	1.00	Hillsboro	Fountain
9	---	2.00	Waynetown	Montgomery
10	---	1.00	Odell	Tippecanoe
10	2.00	---	Attica	Fountain
10	---	1.00	Williamsport	Warren
10	---	1.00	Boswell	Benton
10	---	1.00	US-52; US-41	Benton
10	---	1.00	Montmorenci	Tippecanoe
10	---	1.00	Klondike	Tippecanoe
11	6.00	---	West Lafayette	Tippecanoe
12	6.00	---	West Lafayette	Tippecanoe
13	1.00	---	West Lafayette	Tippecanoe
13	---	1.00	Rossville	Clinton
13	1.00	---	Frankfort	Clinton
13	---	1.00	Pike	Boone
13	---	1.00	Lebanon	Boone

TABLE 18. (continued)

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
14	6.00	---	Frankfort	Clinton
15	4.00	---	Lebanon	Boone
15	---	1.00	Lizton	Hendricks
15	---	1.00	Jamestown	Boone
15	---	2.00	New Ross	Montgomery
16	1.00	---	Pittsboro	Hendricks
16	1.00	---	Brownsburg	Hendricks
16	3.00	---	Plainfield	Hendricks
17	2.00	---	Danville	Hendricks
17	1.00	---	Avon	Hendricks
17	1.00	---	Belleville	Hendricks
17	1.00	---	Stilesville	Hendricks

NOTE: The 9 traffic signals in Crawfordsville are used as safety valves.

TABLE 19. OPTIMAL SEQUENCE OF TRAFFIC SIGNALS AND FLASHERS FOR PAINTING OPERATIONS

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
1	---	3.00	Coalmont	Clay
1	---	2.50	Lewis	Vigo
2	---	1.50	Lewis	Vigo
2	---	4.00	Blackhawk	Vigo
3	2.00	---	Plainfield	Hendricks
4	---	1.00	Jamestown	Boone
4	---	1.00	Lizton	Hendricks
4	1.00	---	Plainfield	Hendricks
4	---	2.00	New Ross	Montgomery
5	1.00	---	Belleville	Hendricks
5	1.00	---	Stilesville	Hendricks
6	1.00	---	Hillsdale	Vermillion
6	---	1.00	US-36; SR-71	Vermillion
6	---	1.00	US-36; SR-63	Vermillion
6	---	1.00	Montezuma	Vermillion
7	1.00	---	US-36; SR-43	Putnam
7	---	1.00	US-36; SR-43	Putnam
7	1.00	---	Bainbridge	Putnam
8	2.00	---	Clinton	Vigo
9	1.00	---	Clinton	Vigo
9	1.00	---	Rockville	Parke

TABLE 19. (continued)

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
10	1.00	---	Rockville	Parke
10	---	1.00	SR-63; Hillsdale	Vermillion
11	1.00	---	West Lafayette	Tippecanoe
11	---	1.00	Montmorenci	Tippecanoe
11	---	1.00	Klondike	Tippecanoe
11	---	1.00	Rossville	Clinton
12	2.10	---	Frankfort	Clinton
13	2.10	---	Frankfort	Clinton
14	2.10	---	Frankfort	Clinton
15	---	1.00	Pike	Boone
15	0.70	---	Frankfort	Clinton
15	1.20	---	Lebanon	Boone
16	0.80	---	Lebanon	Boone
16	---	1.00	Hillsboro	Fountain
17	2.00	1.00	Lebanon	Boone
18	2.00	1.00	Greencastle	Putnam
19	2.00	---	Greencastle	Putnam
20	1.00	---	US-40; SR-43	Putnam
20	1.00	---	Danville	Hendricks

TABLE 19. (continued)

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
21	---	1.00	Waynetown	Montgomery
21	1.00	---	Avon	Hendricks
21	1.00	---	Danville	Hendricks
22	1.00	2.00	Covington	Fountain
22	---	2.00	Sterling	Fountain
22	---	1.00	Waynetown	Montgomery
23	1.00	1.00	Putnamville	Putnam
23	---	1.00	Cloverdale	Putnam
23	---	1.00	US-231; SR-67	Owen
24	2.25	---	West Lafayette	Tippecanoe
25	2.25	---	West Lafayette	Tippecanoe
26	2.25	---	West Lafayette	Tippecanoe
27	2.25	---	West Lafayette	Tippecanoe
28	2.25	---	West Lafayette	Tippecanoe
29	0.75	---	West Lafayette	Tippecanoe
29	---	1.00	US-52; US-41	Benton
29	---	1.00	Boswell	Benton
29	---	1.00	Williamsport	Warren
30	2.00	---	Attica	Fountain
30	---	1.00	Odell	Tippecanoe

TABLE 19. (continued)

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
31	1.75	---	West Terre Haute	Vigo
32	1.25	---	West Terre Haute	Vigo
32	0.50	---	East Glenn	Vigo
33	0.50	---	East Glenn	Vigo
33	1.00	---	Seelyville	Vigo
33	---	1.00	Brazil	Vigo
34	2.00	---	Brazil	Vigo
35	2.00	---	Brazil	Vigo
36	2.00	---	Brazil	Vigo
37	2.00	---	Brazil	Vigo
38	2.00	---	Brazil	Vigo
39	2.00	---	Brazil	Vigo
40	1.00	---	Rockville	Parke
40	---	1.00	Shirkieville	Vigo
40	---	1.00	Williamstown	Vigo
41	1.00	---	Pittsboro	Hendricks
41	1.00	---	Brownsburg	Hendricks

NOTE: The 9 traffic signal installations in Crawfordsville are used as safety valves.

The proper operation of the maintenance sequencing presented in this section is predicated on two procedural techniques. The nine traffic signals in Crawfordsville are necessary to absorb the unused work times because the maintenance scheduling has been performed with 85th-percentile work times. Scheduling maintenance operations with the 85th-percentile work time increases the possibility of the activity scheduled for an eight-hour day being completed in less times. If this situation arises, the maintenance crews finish the day by maintaining the traffic signals in Crawfordsville. At the end of the maintenance cycle those traffic signals in Crawfordsville that have not been maintained receive scheduled preventive maintenance.

The other consideration for the maintenance sequencing is concerned with the use of fractions of traffic signal and flasher installations for the painting operation. The lengthy work time required for the painting operations necessitated this procedure for scheduling work to insure that the time available each day is fully utilized. Because the signal operation is not dependent upon the painting operation, it is possible to leave a signal installation partially painted and return the following working day for the completion of this task.

Contract Versus State Personnel

The comparison of maintenance performed by State personnel versus contract was performed to evaluate the alternate means of arranging traffic signal and flasher maintenance. The analysis was limited to Lafayette, Terre Haute, and West Lafayette because in these cities the traffic signals and flashers were maintained on a contracted basis.

The comparison of State versus contracted maintenance was performed for three alternatives. The first assigned all maintenance operations to subcontractors, and the second option designated the State personnel responsible for preventive maintenance and the subcontractor for corrective maintenance. State personnel were scheduled to perform the preventive and corrective maintenance operations in Lafayette, Terre Haute, and West Lafayette in the third alternative. The anticipated annual costs of these maintenance options were computed, and the results of these calculations are summarized in Table 10.

Inspection of the results of the annual cost calculations reveals that maintenance performed by contractors is less expensive than the same work done by State personnel. The annual cost of the option permitting the State to perform the preventive tasks and the subcontractor corrective tasks was between the two alternatives mentioned above. The subcontracted work is less expensive than the same work done by

State personnel because the hourly maintenance costs for the state are almost twice those for the contractor. In addition, the travel time for the state forces to the site of the maintenance is about ten times longer than the travel time for the various contractors.

There is a reservation concerning the decision to allocate the maintenance work to contractors. The maintenance programs in Lafayette and Terre Haute are not considered adequate because no preventive maintenance programs are carried out in these cities. This situation produces a large number of lamp failures, and the potential hazards to the motorists and pedestrians are higher than when preventive maintenance operations are scheduled.

A preventive maintenance program must be used in the subcontracted areas as well as in the remainder of the district to insure proper traffic signal and flasher operation. Two alternatives are available to the Indiana State Highway Commission concerning preventive maintenance operations in the subcontracted areas. The State personnel can perform the preventive operations while the contractor is assigned the necessary corrective maintenance. This procedure is currently used in West Lafayette with reasonable success. Also, the State can prepare maintenance contracts prescribing that routine maintenance be performed by the contractors. This technique insures that a preventive maintenance program is being followed.

The advisability of allowing contractors to perform all of the maintenance activities in the study district has certain limitations. Unless the signals are grouped together, little benefit results from any savings in travel times. A reliable contractor may not be interested in maintaining the traffic signals and flashers if the locations are widely dispersed. A State maintenance force with various equipment is already available for signal maintenance because the State is responsible for other traffic maintenance activities besides traffic signal and flasher operations. Therefore, the use of subcontractors for all traffic signal and flasher maintenance activities in the Crawfordsville district is not recommended. Consideration should be given to the establishment of a contracted maintenance agreement for the City of Brazil because a sufficient concentration of traffic signals was observed in this urban are to make subcontracted maintenance economical.

Staffing

This part of the maintenance problem was concerned with determining the size of the maintenance staff necessary for effective traffic signal and flasher operation. The analysis of the staffing problem was limited to the portion of the maintenance district that is the responsibility of the State personnel. The traffic signal and flasher maintenance

operations in Lafayette, Terre Haute, and West Lafayette are not included in the staffing analysis because it was previously determined that traffic signal maintenance operations in these cities are most economically maintained on a contracted arrangement.

The analysis of the staff necessary to provide adequate traffic signal and flasher maintenance was determined by considering the following factors:

1. The failure probabilities expressed in Table 11,
2. The average daily repair times,
3. The anticipated time required to perform the preventive maintenance operations, and
4. The suitability of certain seasons for preventive maintenance operations.

The number of days available per year for preventive maintenance were calculated by multiplying the probabilities of no failures occurring in a day times the number of days expected for each failure condition. For the condition when flasher failures are expected, the probability of no failures presented in Table 11 was 0.559, and the length of the observed period of flasher failures was 90 days. Therefore, 40 days in this 90-day interval are not available for routine maintenance operations. For the remaining 275 days of the year, 90 additional days were subtracted because the winter season, extending from the first of December through the first of March,

was not considered satisfactory for preventive maintenance operations. The number of failures were not calculated for the winter season, because the entire period has been removed from consideration for preventive maintenance operations. Therefore, the probability of no failures per day is 0.674 (Table 11) for the remaining 185 days of the year, and the time not available for preventive maintenance was calculated as 61 days. To complete the determination of the time available for routine or preventive maintenance, all failures were assumed to be corrected during the working day in the five-day work week. Any day in which a failure occurred was not considered available for preventive maintenance operations. The result of these limitations is to reduce the work year to 260 days, of which only 69 are available for preventive maintenance.

The preventive maintenance operations require 17 days per cycle (Table 14) for changing the lamps and cleaning the controller and 21 days per year (Table 15) for the painting operations if a two-year painting cycle is employed. Therefore, depending on the lamp replacement policy of one or two cycles per year, 38 or 55 days are required per year, respectively, for the preventive maintenance operations. One maintenance crew can successfully perform the preventive and corrective maintenance operations for the Crawfordsville district.

Because the traffic signal maintenance personnel are also responsible for traffic signal modernization, installation of new traffic signals and flasher complexes, and rebuilding controllers and other signal appurtenances, a single two-man crew is not totally sufficient. A three-main maintenance team would provide the most effective maintenance crew. One man is charged with the responsiblity of rebuilding the controllers and the other repair tasks requiring a high degree of technical skill. The remaining men are assigned the preventive maintenance operations and the less difficult repair tasks.

SUMMARY OF RESULTS AND CONCLUSIONS

The following results and conclusions were derived from this analysis of traffic signal and flasher operations for the Crawfordsville maintenance district in the State of Indiana. The findings were classified under the categories of general conclusions and of results applicable to the Crawfordsville maintenance district.

1. General conclusions

   a. A scientifically determined maintenance program was formulated for traffic signals and flashers using systems analysis techniques. Such a program includes determining the optimal lamp replacement interval, calculating the shortest route for performing the preventive maintenance, and staffing the work crew necessary to insure proper signal operation.

   b. The use of a preventive maintenance program affords certain economic advantages and improves the safety of an interesection because the probability of a failure is reduced.

   c. Lamps with long-rated lives are recommended because their opration is less costly and the anticipated numbers of failures per unit time

are smaller than for bulbs with short lamp lives.

d. An adequate maintenance record system is mandatory for the economic and efficient scheduling of realistic traffic signal and flasher maintenance.

2. Results applicable to the Crawfordsville maintenance district.

a. The relationship expressing the distance traveled in minutes for a typical maintenance trip in the district is:

$$Y_C = 7.765 + 1.437X$$

where

Y_C = travel time in minutes, and

X = distance traveled in miles.

b. The average work times for various preventive maintenance operations are:

	Traffic signal	Flasher
Change lamps	40 min	13 min
Paint	133 min	37 min
Change lamp and paint	173 min	50 min

c. The mean work times for various corrective maintenance operations are:

	Traffic signal	Flasher
Internal	55 min	23 min
Minor external	21 min	16 min
Major external	120 min	57 min

d. The average lamp replacement costs are $0.84 for replacing a lamp in a group replacement program and $18.38 for replacing a lamp at failure.

e. The combined rate (internal, minor external, and major external) for traffic signals was reasonably represented by a Poisson distribution with a mean of 0.0063 failures per day per signal.

f. All flasher failures occurred within a 90-day period with no discernible pattern of malfunctions.

g. The optimum lamp replacement curve was used to indicate the proper interval for scheduling group lamp replacements.

h. In concurrence with American Association of State Highway Officials specifications the use of 6000-hr lamps with a group replacement schedule of six-months is recommended for the most economical preventive maintenance program.

i. The painting and the lamp replacement and controller maintenance are scheduled as separate maintenance

operations to provide sufficient flexibility in the scheduled preventive operations for unpredictable occurrence of failures and poor weather conditions.

j. The use of subcontractors to perform preventive and corrective maintenance operations is advised only for locations where the signal installations are not widely dispersed.

k. The staff required in the Crawfordsville district for the traffic signal and flasher maintenance operations consists of one signal technician qualified to make major controller repairs and two technicians who perform the preventive maintenance and minor-repair tasks.

SUGGESTIONS FOR FURTHER RESEARCH

The findings of this investigation have indicated several possibilities for further research. The following items are suggested for additional study.

1. The effect of various preventive maintenance tasks on the reliability of controller operation should be determined. The results of the study would indicate an advisable maintenance program to maximize the effective use of controllers.
2. A study should be performed to correlate specific signal failures to seasonal variations. The correlations could then be studied, and recommendations made concerning scheduling specific preventive maintenance operations on a seasonal basis.
3. Inventory techniques should be used to study the problems involved in providing sufficient controller replacements and other spare parts to permit satisfactory traffic signal and flasher operation.
4. The costs of signal failures in terms of accidents, delays, inconveniences, and loss of utility should be calculated to permit a complete economic study of traffic signal maintenance problems.

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APPENDICES

APPENDIX A

FORTRAN IV PROGRAM TO DETERMINE THE OPTIMUM LAMP REPLACEMENT TIME

This appendix is a review of the significant features of the lamp replacement program to enable the reader to alter the model to fit individual situations. All line numbers refer to the internal formula numbers presented on the right side of Table 20.

Line	
1, 2	Average rated life and standard deviation (percentage basis), reduced 10 percent for normal field conditions.
3, 4	Group and replacement at failure costs for the Crawfordsville district.
5, 6, 7, 8	Annual lamp burning times presented as in Table 2.
14	Indicates the percentages of rated life starting at 40 percent and incrementing by 5 percent to 150 percent.
23, 82	Indicates the rated lamp lives over the range of 2000 to 8000 hr in increments of 1000 hr.

The data for this program are G(z) values of a normal distribution whose standard score (Z) values range from -0.01 to -4.00. The format for the 399 values for G(z) is F5.5.

TABLE 20

FORTRAN IV PROGRAM TO DETERMINE THE OPTIMUM LAMP REPLACEMENT TIME

```
      DIMENSION ZTABLE(500)
      REAL LIFE
      REAL MEAN
      MEAN=90.0
      STDEV=22.5
      GROUP=0.84
      ONCALL=18.38
      RED=4380.0
      AMBER=700.0
      GREEN=3680.0
      FLASH=5080.0
  150 FORMAT(F5.5)
    1 FORMAT(/////,10X,26HTHESE COMPUTATIONS ARE FOR,2X,F4.0,2X,21HPERCE
     1NT OF RATED LIFE)
    2 FORMAT(///,5X,11HRATED LIFE,5X,11HACTUAL LIFE,3X,3HRED,5X,5HGREEN,
     15X,5HAMBER,5X,7HFLASHER)
    3 FORMAT(42X,16HCHANGES PER YEAR)
    4 FORMAT(/,6X,F6.0,10X,F6.0,4X,F5.1,4X,F5.1,5X,F5.1,6X,F5.1)
    5 FORMAT(//,10X,52H7 IS NOT SIGNIFICANT ASSUME LAMP BURNS ENTIRE PER
     1IOD)
    6 FORMAT(/,10X,16HCOST PER LAMP IS,2X,F6.3)
  200 FORMAT(10X,47HTHE COST PER HOUR OF A LAMP ON THIS REPLACEMENT)
  201 FORMAT(10X,11HSCHEDULE IS,3X,F10.4)
  202 FORMAT(/,15X,23HTHE RATED LAMP LIFE IS,2X,F5.0,2X,5HHOURS)
  203 FORMAT(///,10X,10HNO OF LAMP,9X,13HCOST PER HOUR,6X,13HCOST PER YE
     1AR)
  204 FORMAT(/,21X,44HASSUMES A LAMP BURNS 100 PERCENT OF THE TIME)
  205 FORMAT(12X,F5.0,13X,F10.4,10X,F10.2)
      READ (5,150)(ZTABLE(I),I=1,400)
    9 DO 100 I=40,150,5
      LIFE=I
      WRITE(6,1)LIFE
      WRITE(6,2)
      WRITE(6,3)
      DO 10 J=2000,8000,1000
      TIME=J
      ATIME=TIME*(LIFE*0.01)
      RC=RED/ATIME
      GC=GREEN/ATIME
      AC=AMBER/ATIME
      FC=FLASH/ATIME
      WRITE(6,4)TIME,ATIME,RC,GC,AC,FC
   10 CONTINUE
      Z=(MEAN-LIFE)/STDEV
      IF(Z-4.0)11,11,99
   11 W=100.0*ABS(Z)+0.5
      INDEX=W
      IF(INDEX.EQ.0)GO TO 85
      FN=ZTABLE(INDEX)
      IF(Z.GT.0.0)FN=1.00-FN
   85 IF(INDEX.EQ.0)FN=0.50
C
C     NORMAL EQUATION
C
      TC=(GROUP/LIFE)
      ZFN=1.0-FN
   12 DO 16 J=2,10
      AVG=J
      AMEAN=AVG*MEAN
      TED=SQRT(AVG)
      ASTDEV=STDEV*TED
      AZ=(AMEAN-LIFE)/ASTDEV
      IF(AZ-4.0)13,13,14
   14 ATC=((ONCALL*(AVG-1.0))/LIFE)*ZFN
      TC=ATC+TC
      GO TO 20
   13 Z=AZ
      W=100.0*ABS(Z)+0.5
      INDEX=W
      IF(INDEX.EQ.0)GO TO 75
      FN=ZTABLE(INDEX)
      FN=1.00-FN
      IF(Z.GT.0.0)FN=1.00-FN
   75 IF(INDEX.EQ.0)FN=0.50
      AFN=FN
      ATC=((ONCALL*(AVG-1.0))/LIFE)*(ZFN-AFN)
      TOM=ZFN-AFN
      ZFN=AFN
   15 TC=ATC+TC
   16 CONTINUE
   20 DO 30 K=2000,8000,1000
      AGE=K
      WRITE(6,202)AGE
      WRITE(6,204)
      WRITE(6,203)
      DO 30 L=200,8000,200
      COUNT=L
      REDD=AGE*LIFE*0.001
      CSTHR=(TC/REDD)*COUNT
      CSTYR=CSTHR*365.0*24.0
      WRITE(6,205)COUNT,CSTHR,CSTYR
   30 CONTINUE
      GO TO 100
   99 WRITE(6,5)
      WRITE(6,6)GROUP
      TC=GROUP/LIFE
      GO TO 20
  100 CONTINUE
      STOP
      END
```

APPENDIX B

FORTRAN IV PROGRAM FOR THE ZIMMER MINIMUM PATH ALGORITHM

The Zimmer minimum path algorithm illustrated in Table 21 was used to compute the shortest distance matrix for the signal nodes in the Crawfordsville district. The effective use of this program is predicated on numbering the signal nodes consecutively starting with the maintenance headquarters as number one. The number 61 at internal formula numbers 36 and 65 refer to the last signal node in the study area. The calculation of the shortest distance matrix for the other cases necessitates substituting 61 for the number of the last signal node.

The data input is in the form (4I10) for the NZONE, NLINK, NHOME, and NSTOP information. NZONE refers to the total number of signal and intersection nodes in the study area, and NLINK is the number of links (A to B and B to A) that were observed in the maintenance area. NHOME and NSTOP refers to the node numbers of the first and last signal nodes. These two nodes specify the minimum path trees that are calculated, one emanating from each signal node.

The remaining data consists of the link and node table KIN, KOUT, AND TLINK prepared for analysis with the following format (2I10, F10.2). KIN refers to the to-node, KOUT the from-node, and TLINK the length of the connecting link. The total number of cards prepared in this fashion equals the number entered for NLINK on the first data card. The order of the data cards is important, the KOUT nodes are arranged in ascending order, and for each group of KOUT nodes the KIN nodes are arranged in an increasing manner.

TABLE 21

FORTRAN IV PROGRAM FOR THE ZIMMER MINIMUM PATH ALGORITHM

```
      DIMENSION IN(1000), IOUT(1000), TLINK(1000), INDEX(300),
     1TSUM(300), NODE(300), DIST(70,70)
    1 FORMAT (4I10)
    2 FORMAT (2I10, F10.2)
    3 FORMAT (1H1, 9X, 7HNHOME =, I4)
    4 READ (5,1) NZONE, NLINK, NHOME, NSTOP                    ,1  ,2  ,3  ,4  ,5  ,6

      DO 5  I=1,NLINK                                          ,7
    5 READ (5,2) IN(I), IOUT(I), TLINK(I)                      ,8  ,9  ,10 ,11
      KEY=1                                                    ,12
      DO 6  I=1,NLINK                                          ,13
      IF (IN(I).NE.KEY)  GO TO 6                               ,14 ,15 ,16
      INDEX(KEY)=I                                             ,17
      KEY=KEY+1                                                ,18
    6 CONTINUE                                                 ,19 ,20
    7 DO 20  I=1,NZONE                                         ,21
   20 TSUM(I)=9999.99                                          ,22 ,23
      TSUM(NHOME)=0.0                                          ,24
      NODE(NHOME)=0                                            ,25
      I=INDEX(NHOME)                                           ,26
    8 KEY1=IN(I)                                               ,27
      KEY2=IOUT(I)                                             ,28
      TIMNEW=TSUM(KEY1)+TLINK(I)                               ,29
      IF (TIMNEW.LT.TSUM(KEY2))  GO TO 12                      ,30 ,31 ,32
    9 IF (I.LT.NLINK)  GO TO 13                                ,33 ,34 ,35
      DO 10  I=1,NZONE                                         ,36
   10 DIST(NHOME,I)=TSUM(I)                                    ,37 ,38
      WRITE (6,3) NHOME                                        ,39 ,40 ,41
      DO 11  I=1,NZONE                                         ,42
   11 WRITE (6,2) I, NODE(I), TSUM(I)                          ,43 ,44 ,45 ,46
      IF (NHOME.EQ.NSTOP)  GO TO 14                            ,47 ,48 ,49
      NHOME=NHOME+1                                            ,50
      GO TO 7                                                  ,51
   12 TSUM(KEY2)=TIMNEW                                        ,52
      NODE(KEY2)=KEY1                                          ,53
      IF (KEY1.LT.KEY2)  GO TO 13                              ,54 ,55 ,56
      I=INDEX(KEY2)                                            ,57
      GO TO 8                                                  ,58
   13 I=I+1                                                    ,59
      KEY3=IN(I)                                               ,60
      IF (TSUM(KEY3).EQ.9999.99)  GO TO 9                      ,61 ,62 ,63
      GO TO 8                                                  ,64
   14 PUNCH 999, ((DIST(I,J), J=1,61), I=1,61)                 ,65 ,66 ,67 ,68 ,69 ,70
                                                               ,71 ,72
      GO TO 4                                                  ,73
  999 FORMAT (14F5.1)
      END                                                      ,74
```

APPENDIX C

FORTRAN IV PROGRAM FOR THE MAINTENANCE SIMULATION MODEL

This model illustrated in Table 22 determined the feasibility of various maintenance alternatives, and the paradigm is predicated on the matrix of minimum distances computed by the Zimmer algorithm. The general usage of this model necessitates changing several statements. The READ statement at internal formula number one should correspond to the output statement of the minimum path algorithm (Internal formula number 65 in Table 21). The travel time estimation and the average work times should correspond with the data collected for each study area. The estimates of travel time and work time are found at internal formula numbers 233 and 232, respectively.

The use of the model requires the proper preparation of data. The matrix of shortest distances calculated by the minimum path algorithm is placed directly behind the data card. Then each feasible solution starts and ends with 1000 written in columns two through five. Feasible solutions are composed of several maintenance tours and the data for each tour is punched on two cards. The first card lists the number of signal nodes visited per day (DO NOT EXCEED 10) and the total numbers of signals and flashers maintained each day. The format for the first card is (I5, 2F5.2). The second data card lists the node numbers of the traffic signals and flashers visited in each tour using the format (10I5). Additional tours are placed behind the first tour until all the tours composing a feasible solution are prepared. Any number of feasible

solutions can be tested at one time by placing 1000 punched in column two through five between each trial.

TABLE 22

FORTRAN IV PROGRAM FOR THE MAINTENANCE SIMULATION MODEL

```
C      THIS PROGRAM DETERMINES THE SERVICING SEQUENCE FOR A GIVEN
C      SET OF SIGNALS SUCH THAT THE DISTANCE TRAVELED IS A MINIMUM.
C
       DIMENSION LIST1(10), LIST2(9), LIST3(8), LIST4(7),
      1LIST5(6), LIST6(5), LIST7(4), LIST8(3), LIST9(2),
      2LIST10(2), LISTX(10), NUMREM(10), ARPERM(80), LINK(80,11),
      3IPROD(10), DIST(70,70), TIME(3), HOURS(3)
       COMMON LIST1, LIST2, LIST3, LIST4, LIST5, LIST6,
      1LIST7, LIST8, LIST9, LIST10, LISTX, NUMREM, ARPERM,
      2LINK, IPROD, DIST
  800 FORMAT(/////,20X,17HDISTANCE TRAVELED,3X,9HWORK TIME)
  801 FORMAT(26X,F8.2,10X,F6.2)
  999 FORMAT (14F5.1)
  998 FORMAT (10I5)
  997 FORMAT (I5, 2F5.2)
  993 FORMAT (25X,F5.2, 9H SIGNALS,, F5.2, 10H FLASHERS.)
  992 FORMAT (/, 12HWORK TIME IS, F4.0, 10H HOURS AND, F4.0,
     124H MINUTES, TRAVEL TIME IS, F4.0, 10H HOURS AND, F4.0,
     227H MINUTES, AND TOTAL TIME IS, F4.0, 10H HOURS AND, F4.0,
     3/, 9H MINUTES.)
 1001 FORMAT (1H1)
  995 FORMAT (1H1,33X,31HTHE FOLLOWING ARE COMPUTATIONS ,
     123HWITH A NEW SET OF DATA.)
  994 FORMAT (//////, 27X, 15HSIGNAL ARRAY IS, 10I5)
   98 FORMAT (//,5X,5HINDEX, 5X, 7HMILEAGE, 10X,
     115HSERVICING ROUTE, /)
   99 FORMAT (4X,I4, F10.2, 10I5)
  100 FORMAT (//, 33HFOR THIS SIGNAL ARRAY, , I7, 8H ROUTES ,
     125HDETAIL, THE GIVEN SET OF , I2, 22H SIGNALS WERE COMPUTED,
     226H OUT OF THE TOTAL POSSIBLE, /, 3HOF , I7, 8H (THESE , I7,
     336H ROUTES INCLUDED ALL UNIQUE ROUTES)., I3, 9H MINIMUM ,
     443HROUTES WERE DETERMINED, OF WHICH THE ABOVE , I2, /,
     512HWERE UNIQUE.)
  102 FORMAT (//, 7X, 34HLINK TABLE SIZE EXCEEDED, RESULTS ,
     116HTHROUGH KUMIND =, I7, 4H ARE)
C
C      DATA INPUT AND THE PRINTING OF OUTPUT HEADINGS FOLLOWS.
C
       READ (5,999) ((DIST(I,J), J=1,61), I=1,61)

 1000 READ (5,997) NUM, SIGNAL, FLASH
       IF (NUM.NE.1000) GO TO 996
       WRITE(6,800)
       WRITE(6,801)DISTND,TOTIM
       DISTND=0.0
       TOTIM=0.0
       WRITE (6,1001)
       WRITE (6,995)
       GO TO 1000
  996 READ (5,998) (LIST1(I), I=1,NUM)
       WRITE (6,994) (LIST1(I), I=1,NUM)
       WRITE (6,993) SIGNAL, FLASH
       IF (NUM.EQ.1) GO TO 3501
C
C      COMPUTATION OF ALL POSSIBLE ROUTES FOLLOWS.
C
       KUMIND=1
       NUMR2=NUM-1
       NUMR3=NUM-2
       NUMR4=NUM-3
       NUMR5=NUM-4
       NUMR6=NUM-5
       NUMR7=NUM-6
       NUMR8=NUM-7
       NUMR9=NUM-8
       IPRODT=1
       DO 885 I=1,NUM
       IPROD(I)=IPRODT*I
  885 IPRODT=IPROD(I)
       KEY56=NUM-1
       KUTOFF=IPROD(NUM)
       DO 886 I=1,KEY56
  886 KUTOFF=KUTOFF-IPROD(I)
       I1=0
  200 I1=I1+1
       LISTX(1)=LIST1(I1)
       CALL NOREM (LIST1, LIST2, NUM, I1)
       I2=0
  201 I2=I2+1
       LISTX(2)=LIST2(I2)
       IF (NUMR2.EQ.1) GO TO 1
       CALL NOREM (LIST2, LIST3, NUMR2, I2)
```

TABLE 22 (CONT.)

```
      I3=0                                                          ,74
  202 I3=I3+1                                                       ,75
      LISTX(3)=LIST3(I3)                                            ,76
      IF (NUMR3.EQ.1)  GO TO 1                                      ,77    ,78    ,79
      CALL NCREM (LIST3, LIST4, NUMR3, I3)                          ,80
      I4=0                                                          ,81
  203 I4=I4+1                                                       ,82
      LISTX(4)=LIST4(I4)                                            ,83
      IF (NUMR4.EQ.1)  GO TO 1                                      ,84    ,85    ,86
      CALL NCREM (LIST4, LIST5, NUMR4, I4)                          ,87
      I5=0                                                          ,88
  204 I5=I5+1                                                       ,89
      LISTX(5)=LIST5(I5)                                            ,90
      IF (NUMR5.EQ.1)  GO TO 1                                      ,91    ,92    ,93
      CALL NCREM (LIST5, LIST6, NUMR5, I5)                          ,94
      I6=0                                                          ,95
  205 I6=I6+1                                                       ,96
      LISTX(6)=LIST6(I6)                                            ,97
      IF (NUMR6.EQ.1)  GO TO 1                                      ,98    ,99    ,100
      CALL NCREM (LIST6, LIST7, NUMR6, I6)                          ,101
      I7=0                                                          ,102
  206 I7=I7+1                                                       ,103
      LISTX(7)=LIST7(I7)                                            ,104
      IF (NUMR7.EQ.1)  GO TO 1                                      ,105   ,106   ,107
      CALL NCREM (LIST7, LIST8, NUMR7, I7)                          ,108
      I8=0                                                          ,109
  207 I8=I8+1                                                       ,110
      LISTX(8)=LIST8(I8)                                            ,111
      IF (NUMR8.EQ.1)  GO TO 1                                      ,112   ,113   ,114
      CALL NCREM (LIST8, LIST9, NUMR8, I8)                          ,115
      I9=0                                                          ,116
  208 I9=I9+1                                                       ,117
      LISTX(9)=LIST9(I9)                                            ,118
      IF (NUMR9.EQ.1)  GO TO 1                                      ,119   ,120   ,121
      CALL NCREM (LIST9, LIST10, NUMR9, I9)                         ,122
      LISTX(10)=LIST1 (1)
C
C     COMPUTATION OF ROUTE LENGTH FOLLOWS.
C                                                                   ,123
    1 ITEM1=LISTX(1)                                                ,124
      ITEM2=LISTX(NUM)                                              ,125
      SUM=DIST(1,ITEM1)+DIST(1,ITEM2)                               ,126
      DO 35 III=1,NUMM                                              ,127
      J=III+1                                                       ,128
      ITEML=LISTX(III)                                              ,129
      ITEMR=LISTX(J)                                                ,130
   35 SUM=SUM+DIST(ITEML,ITEMR)
C
C     THE FOLLOWING SUBPROGRAM DETERMINES IF THE LENGTH OF THE
C     NEW ROUTE IS LESS THAN THAT OF THE PREVIOUS MINIMUM.
C                                                                   ,131   ,132
      IF (KUMINC.EQ.1)  GO TO 38                                    ,133   ,134   ,135
      TRIP=ABS(SUM-ARPERM(1))                                       ,136
      IF (TRIP-0.0001) 39,340,340                                   ,137
   39 INDEX=INDEX+1                                                 ,138
      IF (INDEX.GE.31) GO TO 42                                     ,139   ,140   ,141
      INDEX=30                                                      ,142
      KUMINC=KUMINC-1                                               ,143
      KEY56=999                                                     ,144
      GO TO 43                                                      ,145
  340 IF(SUM.GT.ARPERM(1))  GO TO 40                                ,146   ,147   ,148
   38 INDEX=1                                                       ,149
   42 ARPERM(INDEX)=SUM                                             ,150
      DO 41 J=1,NUM                                                 ,151
   41 LINK(INDEX,J)=LISTX(J)                                        ,152   ,153
      LINK(INDEX,11)=KUMINC                                         ,154
   40 IF (KUMINC.EQ.KUTOFF) GO TO 43                                ,155   ,156   ,157
    2 KUMINC=KUMINC+1                                               ,158
      GO TO  (43,251,252,253,254,255,256,257,258,259),NUM           ,159
  259 IF (I9.NE.NUMR9)  GO TO 208                                   ,160   ,161   ,162
  258 IF (I8.NE.NUMR8)  GO TO 207                                   ,163   ,164   ,165
  257 IF (I7.NE.NUMR7)  GO TO 206                                   ,166   ,167   ,168
  256 IF (I6.NE.NUMR6)  GO TO 205                                   ,169   ,170   ,171
  255 IF (I5.NE.NUMR5)  GO TO 204                                   ,172   ,173   ,174
  254 IF (I4.NE.NUMR4)  GO TO 203                                   ,175   ,176   ,177
  253 IF (I3.NE.NUMR3)  GO TO 202                                   ,178   ,179   ,180
  252 IF (I2.NE.NUMR2)  GO TO 201                                   ,181   ,182   ,183
  251 IF (I1.NE.NUM)    GO TO 200
C
C     THIS SUBPROGRAM IDENTIFIES AND MARKS ANY NON-UNIQUE
C     MINIMUM PATHS.
C                                                                   ,184   ,185   ,186
   43 IF (INDEX.EQ.1) GO TO 46                                      ,187   ,188   ,189
      KEY98=INDEX-1                                                 ,190
```

TABLE 22 (CONT.)

```
      DO 45 I=1,KEY98                                                  ,191
      KEY96=I+1                                                        ,192
      DO 45 K=KEY96,INDEX                                              ,193
      IF (LINK(I,1).EQ.-1.OR.LINK(K,1).EQ.-1) GO TO 45                 ,194  ,195  ,196
      KEY97=NUM+1                                                      ,197
      DO 44 L=1,NUM                                                    ,198
      KEY97=KEY97-1                                                    ,199
   44 IF (LINK(I,L).NE.LINK(K,KEY97)) GO TO 45                         ,200  ,201  ,202  ,203
      LINK(K,1)=-1                                                     ,204
   45 CONTINUE
C
C     OUTPUT OF COMPUTATIONAL RESULTS FOLLOWS.
C                                                                      ,205  ,206  ,207
      IF (KEY56.NE.999)  GO TO 46                                      ,208  ,209  ,210
    3 WRITE (6,102) KUMIND                                             ,211  ,212  ,213
   46 INCRED=0                                                         ,214
 3502 WRITE (6,98)                                                     ,215  ,216
      DO 47 I=1,INDEX                                                  ,217
      IF (LINK(I,1).EQ.-1) GO TO 47                                    ,218  ,219  ,220
      WRITE (6,99) LINK(I,11), ARPERM(I), (LINK(I,J), J=1,NUM)         ,221  ,222  ,223  ,224  ,225  ,2[illegible]

      INCRED=INCRED+1                                                  ,227
   47 CONTINUE                                                         ,228  ,229
      WRITE (6,100) KUMIND, NUM, IPRODT, KLTLFT, INDEX, INCRED
C
C     THE FOLLOWING SUBPROGRAM COMPUTES THE TIME CONSUMED IN
C     SERVICING THE GIVEN SET OF SIGNALS.
C                                                                      ,230  ,231  ,232
      TIME(1)=174.5*SIGNAL+30.0*FLASH                                  ,233
      TIME(2)=7.5+1.44*ARPERM(1)                                       ,234
      TIME(3)=TIME(1)+TIME(2)                                          ,235
      DO 301  I=1,3                                                    ,236
  301 HOURS(I)=0.                                                      ,237  ,238
      DO 302  I=1,3                                                    ,239
  303 IF (TIME(I).LT.60.0)  GO TO 302                                  ,240  ,241  ,242
      TIME(I)=TIME(I)-60.0                                             ,243
      HOURS(I)=HOURS(I)+1.0                                            ,244
      GO TO 303                                                        ,245
  302 CONTINUE                                                         ,246  ,247
      WRITE (6,942) (HOURS(I), TIME(I)), I=1,3)                        ,248  ,249  ,250  ,251  ,252
      DISTNC=DISTNC+ARPERM(1)                                          ,253
      TOTIME=(HOURS(2)*TIME(2))/60.0                                   ,254
      GO TO 1000                                                       ,255
 3501 INDEX=1                                                          ,256
      LINK(1,11)=1                                                     ,257
      LINK(1,1)=LIST1(1)                                               ,258
      MOF=LIST1(1)                                                     ,259
      ARPERM(1)=0.0*DIST(1,MOP)                                        ,260
      KUMIND=1                                                         ,261
      IPRODT=1                                                         ,262
      KLTLFT=1                                                         ,263
      GO TO 46                                                         ,264
      END                                                              ,265




      SUBROUTINE NCREM (LISTIN, LISTOU, NUMBER, NODE)
      DIMENSION LIST1(10), LIST2(9), LIST3(8), LIST4(7),
     1LIST5(6), LIST6(5), LIST7(4), LIST8(3), LIST9(2),
     2LIST10(2), LISTX(10), NUMBEM(10), ARPERM(80), LINK(80,11),
     3IPROD(10), DIST(70,70), LISTIN(10), LISTOU(10)
      COMMON LIST1, LIST2, LIST3, LIST4, LIST5, LIST6,
     1LIST7, LIST8, LIST9, LIST10, LISTX, NUMBEM, ARPERM,
     2LINK, IPROD, DIST
C
C     SUBROUTINE NCREM MAKES A LIST AT EACH STEP OF COMPUTATION
C     OF THE REMAINING SIGNALS WHICH HAVE NOT PREVIOUSLY BEEN
C     SERVICED.
C
      DO 58 I12=1,NUMBER                                               ,1
      IF (I12-NODE) 57,58,59                                           ,2
   57 J=I12                                                            ,3
      GO TO 60                                                         ,4
   59 J=I12-1                                                          ,5
   60 LISTOU(J)=LISTIN(I12)                                            ,6
   58 CONTINUE                                                         ,7  ,8
      RETURN                                                           ,9
      END                                                              ,10
```